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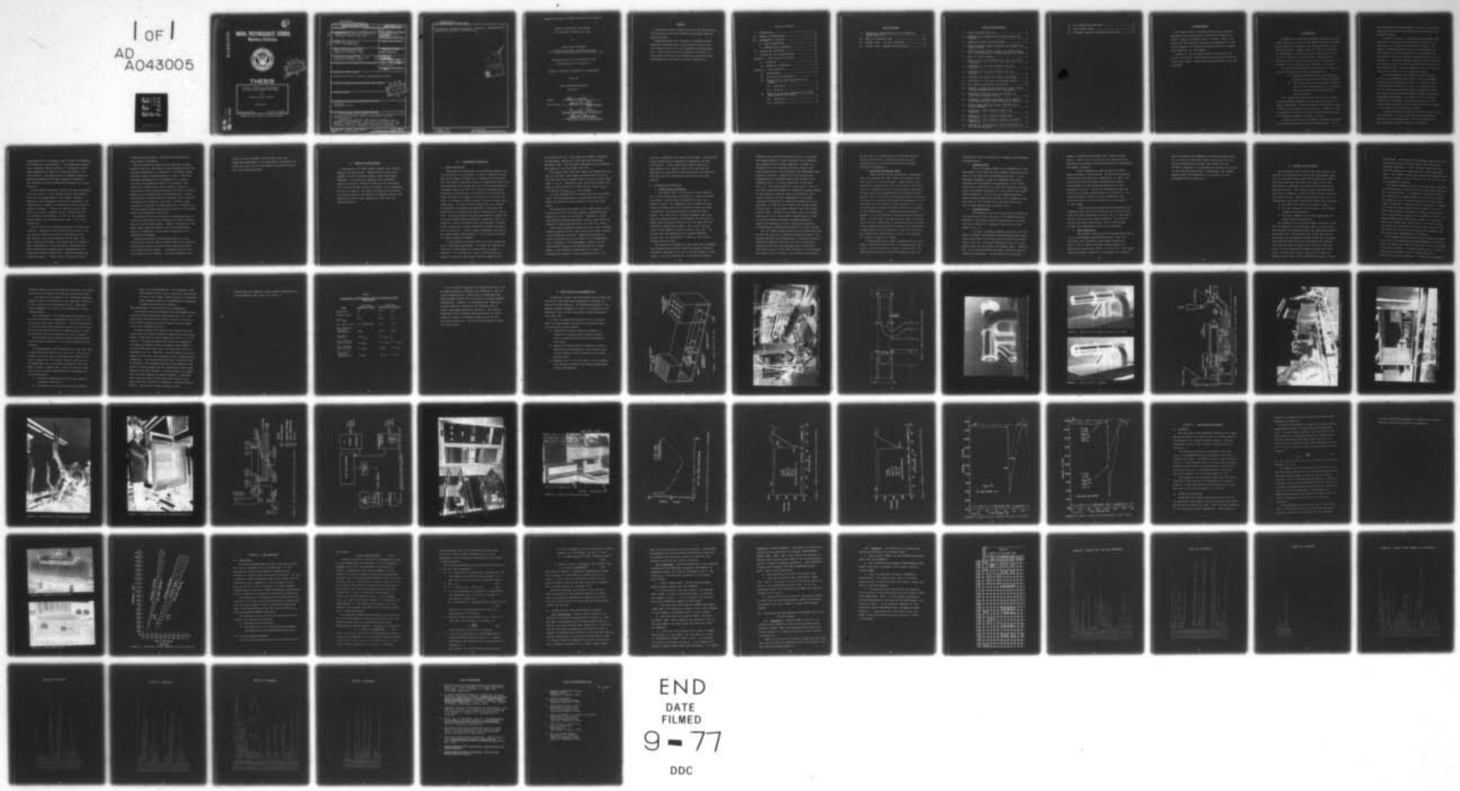

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

DESIGN, CONSTRUCTION AND TESTING
OF A SUB-SCALE TURBOJET TEST CELL

by

Holden Willets Hewlett

March 1977

Thesis Advisor: David W. Netzer

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Design, Construction and Testing of a Sub-scale Turbojet Test Cell

by

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Lieutenant Commander, United States Navy
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Submitted in partial fulfillment of the requirements for the degree of

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The author wishes to recognize the patient, tenacious, optimistic advice and support of his thesis advisor and friend, Associate Professor David W. Netzer. Much of the credit for the successful operation and completion of this initial segment of a promising project belongs to a superb aero-technician, Mr. Pat Hickey.

Foremost in the meaningful support received for the project and course of instruction at NPS was my devoted and loving wife, Nancy, without whose encouragement I would have succumbed.

I. INTRODUCTION

Turbojet test cells are fixed-base installations generally located at aircraft maintenance facilities to employ during the ground testing of jet engines prior to operational service. A typical test cell (Fig. 1) is usually an independently housed rectangular shaped building with an inlet stack and an exhaust stack. There are many different variations of the basic design depending on the equipment to be tested and the objective of the tests.

The Navy's construction and utilization of test cells may be attributed to two basic considerations:

(a) Engine operation free from detrimental industrial or environmental foreign objects.

(b) Performance monitoring and engine modifications to meet specifications in an environment which closely simulates installed engine operation.

The object of an adequate cell design is to achieve optimum operating conditions with a minimum of environmental disturbance. Pollution control is currently a major problem in the operation of test cells. A test cell must be designed to control or minimize either noise pollution or atmospheric chemical pollution, or both.

Uniform flow with low turbulence intensity is desired to facilitate accurate performance measurements. It is

also desirable to have designed-in flexibility for future modifications which may be required to the test cell for expanded testing.

As shown in Figure 1, the engine is positioned somewhere near the center of the U-shaped cell which allows the inlet air to develop a uniform flow profile. The engine consumes only part of the air; the remainder is entrained by the engine exhaust which is directed into the augmentor tube and expelled through the stack to the atmosphere. The engine exhaust venting into the augmentor tube acts as an air ejector which pulls secondary air into the augmentor tube. The secondary air acts as a coolant as well as a diluent for the exhaust products.

The spacing between the engine tail pipe and the inlet to the augmentor tube can be a crucial parameter to proper engine operation since it is a primary factor in determining secondary air flow. Too much secondary air flow may cause excessive pressure gradients between the engine inlet and exhaust planes leading to inaccurate performance measurement. In addition, cell structural limits may be exceeded. Not enough secondary air may allow exhaust back flow to the engine inlet and hot spots in the augmentor tube and exhaust stack.

Today's stringent standards to preserve the quality of the environment are acute cell design considerations. Secondary air entrainment into the engine exhaust of a non-afterburning engine reduces the pollutant

concentrations in the exhaust stack but does not appreciably change the total emittants. With afterburning operations, secondary and/or tertiary air entrainment and/or water quenching can affect the total emittants in the exhaust stack. The optimization of augmentor design and quenching methods has not been adequately determined with chemical and noise pollution minimization as a major criterion.

Other pollution abatement methods have been considered and tried (Ref. 1). They include exhaust gas scrubbing, which may be accomplished by water droplet adhesion, mechanical grid entrapment or electronic ionization, and combinations of baffles to disperse the exhaust gases for acoustic treatment. "Dry-house" designs are also being built and studied. Examples are the "Hush House" such as installed at NAS Miramar, Ca.(Ref. 2) for installed engine testing, and a Coanda design (Ref. 3) for noise suppression.

Many of the current abatement methods are complex and, therefore, expensive to both construct and operate. For the large jet engines and huge air consumption rates they require, large scale hardware must be used. For these large scale engines, fuel supply and cost becomes a major consideration of cell operation. Maintenance of large installations requires major considerations for scheduling, periodic replacement of damaged hardware and financial support. A major portion of support must be

attributed to attracting, qualifying and maintaining a large staff of personnel.

Various analytical techniques for modeling a typical turbojet test cell are possible using mathematical and computerized simulations. An example is the study by Hayes and Netzer (Ref. 4) which concludes in part, "The model provides axisymmetric flow visualizations in turbojet test cells and augmentor tubes for low subsonic flow conditions. These can be used to identify regions of recirculation and to assess the amount of mixing occurring between engine exhaust gases and secondary air. Optimum locations for pollution sampling equipment can be selected by examining the numerical solutions." However, model validation is required and additional work is required for the high engine exhaust velocities which occur for military thrust and afterburning conditions.

Representative air flow rates can be determined for the models from known data of an existing full scale operating facility such as NARF Alameda. However, validation of computer models requires detailed flow field measurements which are impractical in full scale facilities due to scheduling and expense.

The above discussion indicates the need for a test facility which can be used to perform design and operating optimization studies to both minimize emitted pollution and validate/improve models. A sub-scale test cell can be utilized for this purpose. With some drawbacks with

regard to scaling effects, the sub-scale test cell offers many advantages - low construction, maintenance and operating costs, ease of instrumentation and data acquisition, and minimum personnel.

II. METHOD OF INVESTIGATION

A one-eighth scale NARF Alameda turbojet test cell was designed and constructed. Engine simulation was accomplished by using a variable bypass, sudden dump ramjet combustor. The ramjet was supplied with the desired amount of air and an identical amount of air was pulled into a simulated engine inlet and dumped to the atmosphere by using an ejector. The engine and test cell were used for initial study of the effects of augmentor location and engine flow rate on cell augmentation ratio and flow characteristics.

III. EXPERIMENTAL APPARATUS

A. DESIGN METHODOLOGY

Construction and operation of a sub-scale turbojet test cell was found to be desirable in order to provide an inexpensive and versatile means for a) studying the effects of test cell design and engine operating conditions on cell flow characteristics and emitted pollution, and b) experimentally validating models for test cell operating characteristics. There were practicalities of construction that guided the design process; for example, the choice of a low cost, sub-scale, air breathing engine realistic enough to obtain meaningful data. Sub-scale turbine engines were too complex and expensive and simply not available; flame tubes and torches did not simulate the airflow conditions of a jet engine. With the readily available compressed air supply from an Allis-Chalmers twelve-stage axial compressor (Fig. 2), a forced air ramjet was chosen which incorporated a variable bypass designed to simulate mixed-flow turbofan engines as well as turbojets. Figure 3 shows a schematic side view of the ramjet engine while Figures 4, 5 and 6 show the ramjet in various stages of assembly.

It was decided to simulate TF-41 test cell conditions with a one-eighth scale model. The scale was selected on the basis of practicality of construction, economy of operation, the available air supply, and the desire to maintain velocities and similar Reynolds numbers to the

full-scale test cell. The engine was scaled in diameter by one-eighth, resulting in the mass flow rate being scaled by 1/64. This was done to maintain flow velocities the same as in the full-scale test cell.

The overall TF-41 test cell length was reduced from 125 feet to 15.6 feet, cell height and width from 18 feet to 2.25 feet and engine diameter from 31 inches to 3.88 inches (Figs. 7, 8, 9). Engine air flow rates for the model were taken as 1/64 of those of a TF-41 engine; namely $\dot{m}_{idle}$ = 1.56 lbm/sec and $\dot{m}_{military}$ = 4.11 lbm/sec.

Once the dimensions of the engine and cell were determined, the associated piping and hardware were sized to supply the system with the required air and fuel flow rates.

The one-eighth scale model, while exhibiting air flow velocities of the full scale versions, reduced Reynolds numbers by a factor of one-eighth. Therefore, results obtained from extensive sub-scale testing still should be compared to those obtained with a few full scale tests.

Yet another difference between the full scale turbojet/turbofan engines and the ramjet (one-eighth scale version) is the combustion pressure. Combustion pressures in today's turbojets are on the order of 10-12 atmospheres and in turbofans, 17-20 atmospheres, whereas the sub-scale ramjet pressures were approximately 2.5 atmospheres. These pressure differences will result in significantly different species concentrations in the

tail pipe, especially for carbon particulates. Particulates in the ramjet must be generated by operating with fuel rich mixtures. Thus, conclusions reached concerning the effects of cell design, engine flow rate and fuel additives on particulate levels emitted from the sub-scale test cell must be validated with some full scale test results.

B. DESCRIPTION OF APPARATUS

1. Ramjet Engine and Piping

The ramjet (Fig. 3) consisted of three sections, two of which constituted the combustor, nozzle and bypass air ducting, and one which simulated the intake of a turbojet engine. The combined airflow through the combustor and bypass duct were balanced to match, as nearly as practical, the suction airflow through the engine intake. The intake was a four-inch diameter steel pipe with two three-inch pipes "goosenecked" off the sides to reduce external profile drag while at the same time providing the required flow area to join to the six-inch suction line leading to the air ejector (Fig. 10). The airflow rate was measured with a standard ASME-type orifice (Ref. 5) installed in a flange in the six-inch, schedule 40 steel pipe.

Two three-inch, schedule 40 steel pipes with accompanying flange mounted orifices supplied combustor (primary) and bypass (secondary) air flow to the aft section of the ramjet. Fuel was injected into the primary air supply

through fifty 0.010-inch diameter holes in a ring manifold approximately 18 inches upstream of the combustor. The combustor was of sudden expansion (or dump) configuration that was designed to hold a flame in the recirculation zone in the combustor can immediately downstream of the step. Ignition of the JP-4 fuel was accomplished by a methane-oxygen torch placed in the combustor wall 1 3/4 inches downstream of the step (Fig. 3). This torch acted as a pilot light in that it was kept burning throughout the combustion process because it was desired to operate over a wide fuel/air ratio range to control the exit temperature of the gases. According to Reference 6, dump burners operated at low pressures, as this one was, exhibit very narrow flammability limits. The primary combustor was a thin-walled inconel tube. By-pass air was used to cool the inconel tube as well as to lower exhaust temperatures in order to further simulate mixed-flow turbofan operation. Primary and secondary air-flow rates were controlled by hand-valves installed downstream of the flow orifices.

The fuel supply system consisted of a pressurized tank of JP-4 jet fuel and a regulated nitrogen pre-load. The pressurized fuel was filtered prior to passing through an electrical solenoid valve and into the ring manifold. Metering of the fuel was accomplished by installing a cavitating venturi in the fuel line prior to the manifold. The function of the venturi was to permit the adjustment

of fuel flow as a function only of upstream pressure. The fuel flow rate vs. upstream pressure was pre-calibrated prior to system installation as further described in Appendix A.

2. Test Cell and Exhaust Stack

Since versatility was considered a major design goal, the separate cell test section and exhaust stack were bolted to twin I-beam rails. These sections were essentially independent of the fixed plumbing and ramjet engine for comparative ease of longtitudinal realignment. The test section was constructed of reinforced 3/4-inch plywood with an inlet flow straightening section consisting initially of 1 1/2-inch thick aluminum honeycombing (1/4-inch mesh) and two layers of window screening (Fig. 11). The installation permitted selective addition or removal of flow straighteners in a slide-in-frame arrangement. In addition, the inlet included a square sheet-aluminum bell-mouth. The cell also included removable sides for engine access and the installation of plexiglass ports to permit visual observation of backflow conditions and photographic documentation of engine operation. Since the model cell was mounted above ground level on rails, the complexity of a vertical intake was avoided.

A plate-steel exhaust stack, separate from the test section, allowed augmentor tube interchangeability and, if desired, the introduction of ambient tertiary air. The stack was fitted with a 45-degree deflection plate and

provided for future installation of exhaust gas measurement instrumentation.

3. Augmentor Tube

One of the basic studies to be conducted with the cell model is the effect of the augmentor tube position and size on flow conditions and augmentation ratio. It was therefore necessary to plan for augmentor tube interchangeability and adequate instrumentation. The initial installation consisted of an eight-inch diameter stainless steel pipe mounted horizontally in the plane of the ramjet engine centerline, with a 2.25-inch space between the engine exhaust nozzle and the mouth of the augmentor tube. The walls of the 4.44 feet long tube were fitted with twelve evenly spaced static pressure ports.

4. Instrumentation.

The sub-scale test cell was fully instrumented for the calculation of air flow rates, cell temperatures and pressures, and velocity profile measurements at the cell entrance, engine inlet, augmentor tube exit and stack exhaust (Fig. 12).

A 24 port, automatic-stepping scanivalve was utilized to "collect" the upstream and downstream static pressures across each of the three airflow measuring orifices (Figs. 7 and 12); the static pressures at the cell inlet, engine inlet, engine exhaust, and exhaust stack. Additionally, the twelve augmentor tube static pressures were fed through the scanivalve. The scanivalve was set up to

measure a differential pressure from a known pressure source. Hence, two of the ports of the scanivalve were relegated to atmosphere and reference pressure respectively for system, "zeroing".

Static temperatures were measured utilizing copper-constantan thermocouples. The airflow measurement calculations required static temperature, so each of the three airflow lines included thermocouples located approximately six pipe diameters downstream of their respective orifices. Additional thermocouple positions included cell inlet, engine exhaust and stack exit. The copper-constantan leads from each thermocouple were routed through an ice-bath reference to an automatic B. & F. data logger.

A Flow Corporation Model MM-2 Micromanometer and traversing pitot tube mounted horizontally twelve inches behind the flow straightener section (Fig. 8) were used to measure the inlet flow velocity profile. The velocity profiles provided indications of flow distortion and allowed cell augmentation ratio to be calculated.

5. Data Acquisition

The automatic data acquisition system consisted of a fully programmable Hewlett-Packard 9830 A desk top Calculator with a HP-9867 B Mass Memory Storage unit and a B. and F. Model SY133 data logger coupled to a paper punch tape printer (Figs. 13, 14 and 15). The system provided automatic scanning of 24 channels of individual

pressure readings and temperature measuring thermocouples. The raw data were punched on paper tape during each run and then entered via a digital tape reader into the HP-9830 A Calculator for processing and storage in the form of both raw and reduced data. Additionally, the HP-9830 system offered the capability of a printout in a pre-programmed format (Appendix B).

IV. RESULTS AND DISCUSSION

The one-eighth scale turbojet test cell facility was designed and constructed to provide an experimental apparatus to validate existing and future analytical models of full scale turbojet test cells with regard to air flow recirculation, augmentor tube variations and exhaust gas pollution control. The sub-scale model was constructed using design judgments involving scaling effects and material practicalities. Testing was performed following the completion of each major construction state which included:

a) The piping for engine air intake and supply.

b) The cell mounting, instrumentation, fuel system hookup and engine firing.

c) The final assembly of the major components for overall system verification.

The balancing of flow rates between the engine intake and the summation of the combustor supply and bypass air was effected with comparative ease for approximate desired conditions; but, when accurate flow rates were desired, the manual valve adjustment process became time consuming. Flow matching conditions were indicated by the HP-9830 Calculator printout following the taking of a data set. While the data acquisition process was smooth and efficient, the operator's manual control of the gate and flapper valves could well be expedited by electric valve

controllers. The control of the flapper valve on the six-inch suction line to the air ejector was found to be extremely sensitive. A very low gear ratio controller would be required for remote control of that particular valve. The overall "cross-talk" sensitivity among the competing air supply lines was found to be very mild and was not considered a problem.

The engine component testing required several attempts and modifications to achieve ignition and stable flame holding without blow-off. A Champion VR-1 spark plug (Fig. 5) was replaced by a methane-oxygen torch (Fig. 3), because the spark plug did not have enough energy to ignite the nearly atmospheric temperature fuel/air mixture. In order to provide the flame stabilization outside of the very narrow dump combustor flammability limits, the torch was left burning during combusion of the JP-4/air mixture. The methane-oxygen torch proved very capable of functioning both as an igniter and a pilot light, but further attention needs to be devoted to the flame position due to the fact that torch blow-off was occurring for combustor air flow rates above approximately 0.8 lbm/sec.

The augmentor tube pressure profiles showed a considerably lower than atmospheric maximum pressure until the decision to restrict the exhaust stack exit with its own dust cover plate was made. An exhaust stack grating to raise the internal pressure by flow resistance will be required for future operations. In addition, the augmentor

pressure profiles also indicated the possibility of leakage around the seal between the augmentor and exhaust stack.

Air ejector noise proved to be a community annoyance, partially due to the position of the laboratory facilities at NPS relative to the surrounding hills. Additional sound suppression will have to be incorporated into the ejector exhaust.

The installation of the plexiglass viewing ports (Fig. 9) proved beneficial in determining engine light off and witnessing normal engine operation. Further modifications to make the plexiglass a permanent part of the cell structure are required with definite attention paid to engine bay access as well as maintaining air tight integrity.

The automatic data acquisition system performed flawlessly and was considered to be a major attribute of the facility.

The micromanometer and traversing pitot tube were used to acquire velocity data at the cell inlet. The velocity profiles indicated that the micromanometer lacked sufficient accuracy due to the small velocity variations and the excessively long time delays required for the manometer to reach a steady value. There are several alternate means of velocity measurements to be attempted for future experiments:

a) A miniature anemometer which has the advantage of relative simplicity.

b) A cylindrical rod that sheds trailing vortices

over a hot wire anemometer. The frequency of the shed vortices may be used to calculate the velocity by use of the Strouhal Number, which is a dimensionless frequency based on the parameters of frequency, cylindrical diameter and velocity.

The disadvantage of this system is its complexity.

The velocity profiles indicated that aerodynamic acceleration occurred around the inlet ramps (Fig. 16). The pitot probe should be moved further aft from the inlet if flat velocity profiles are to be used for ease of determining cell augmentation ratio.

Pressure profiles were obtained for several flow conditions and two separate augmentor tube-to-engine spacings, namely, flush and two inches separation (Figs. 16, 17, 18 and 19). The profiles showed that there was essentially no change in pressure within the exhaust stack except at the very high flow rates, due to the fact that the stack resistance was low. Therefore, one may conclude that the pressure at the exit of the augmentor tube is approximately atmospheric. The pressure profiles show a sharp decrease in pressure at the entrance section of the augmentor tube. Since the first pressure tap was located four inches downstream of the tube entrance, it was not possible to determine the exact location of minimum pressure. Additional static pressure ports in the first four inches of augmentor tube are desirable to establish a refined pressure profile. The initial results obtained in this

investigation are compared to the computer predictions of the Hayes/Netzer study (Ref. 4) in Table 1.

TABLE I

COMPARISONS OF EXPERIMENTAL DATA TO ANALYTICAL MODEL PREDICTIONS

Item	Full Scale Analytical Model	Sub-Scale Experimental Results	
Engine Dia.	25"	3.5"	3.5"
Augmentor Dia.	6'	8"	8"
D_{aug}/D_{eng}	2.88	2.29	2.29
Aug. Ratio (A.R.)	0.5 (specified)	0.72	0.61
Eng. Operating Condition (Simulated)	IDLE	IDLE	IDLE
Aug.-Eng. Spacing	.25 D_{aug}	.25 D_{aug}	0
Min. Pressure Point in Aug.	.4 D_{aug}	0-.5 D_{aug}	0-.5 D_{aug}
Max. Pressure Point in Aug.	3.2 D_{aug}	4 D_{aug}	4.5 D_{aug}
Min. to Max. Pressure Differential	.36 psi	.14 psi	.15 psi

In the computer simulation the augmentation ratio must be specified and was therefore not identical to that obtained experimentally. These initial comparisons show good agreement except for the minimum to maximum pressure differential. However, as indicated above, additional pressure taps are required in the augmentor tube to locate and measure the minimum pressure. The computer predictions also indicated negligible effect of engine-augmentor spacing on augmentor pressure rise for the low thrust conditions. The initial data appear to agree with this result.

V. CONCLUSIONS AND RECOMMENDATIONS

A sub-scale turbojet test cell model has been built and the initial tests have been completed to determine its operating characteristics. The mechanical aspects of the facility operate adequately to meet the objectives of the experiment, and the data acquisition system complements the system well.

In order to improve the operation of the sub-scale model for experimental validation of analytical models the following are recommended:

a) Improve the velocity measuring equipment to establish an accurate inlet velocity profile which is needed for determining the augmentation ratio.

b) Refine the pressure profile analysis by placing additional instrumentation in the entrance area of the augmentor tube to establish the minimum pressure point.

c) Establish the "well mixed" point in the augmentor tube through horizontal and vertical temperature profile measurements.

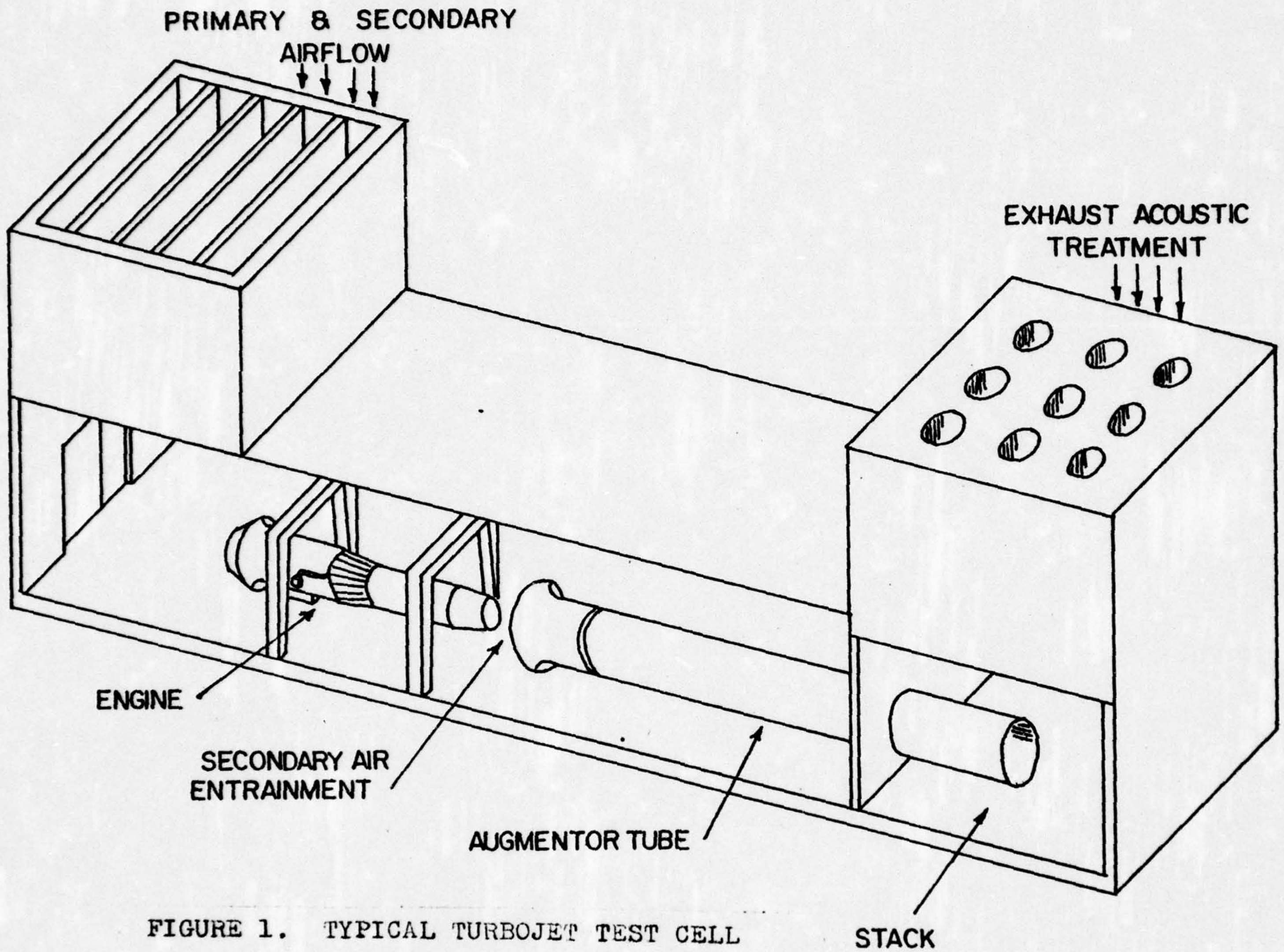


FIGURE 1. TYPICAL TURBOJET TEST CELL

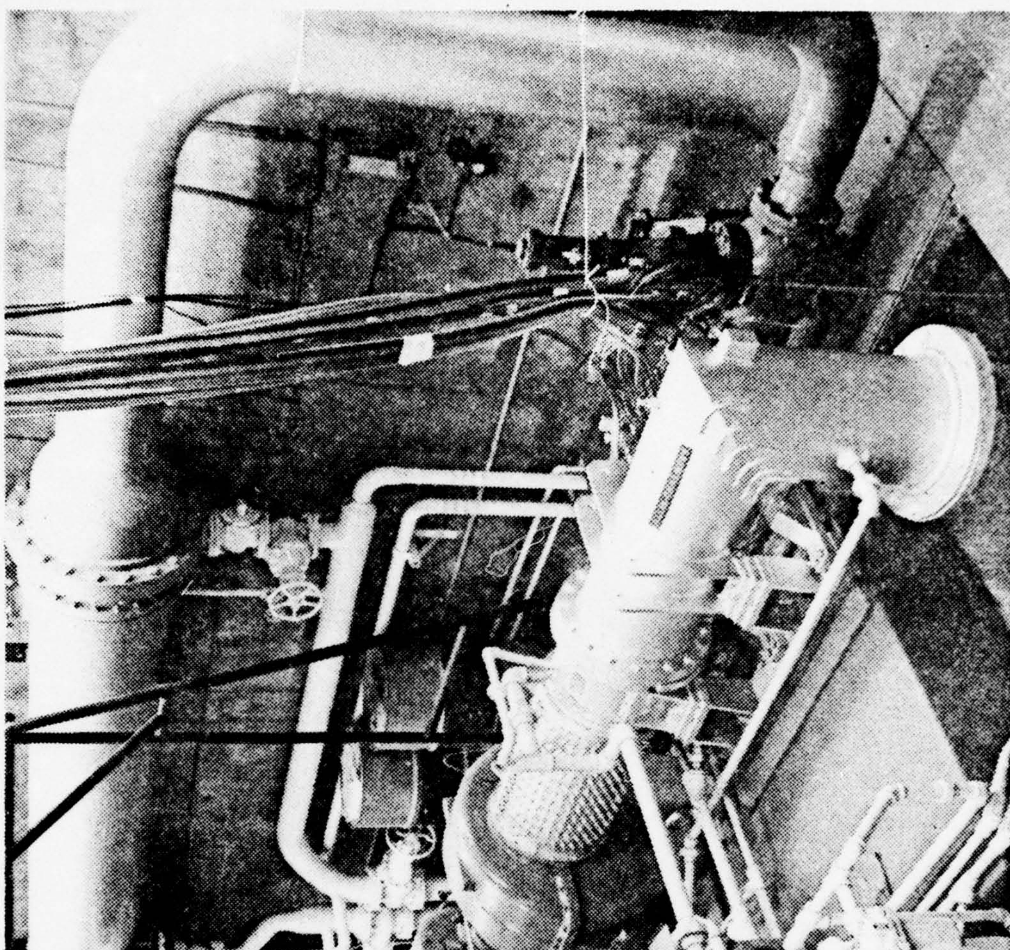


FIGURE 2. PHOTOGRAPH OF 12-STAGE ALLIS CHALMERS AXIAL COMPRESSOR PLANT

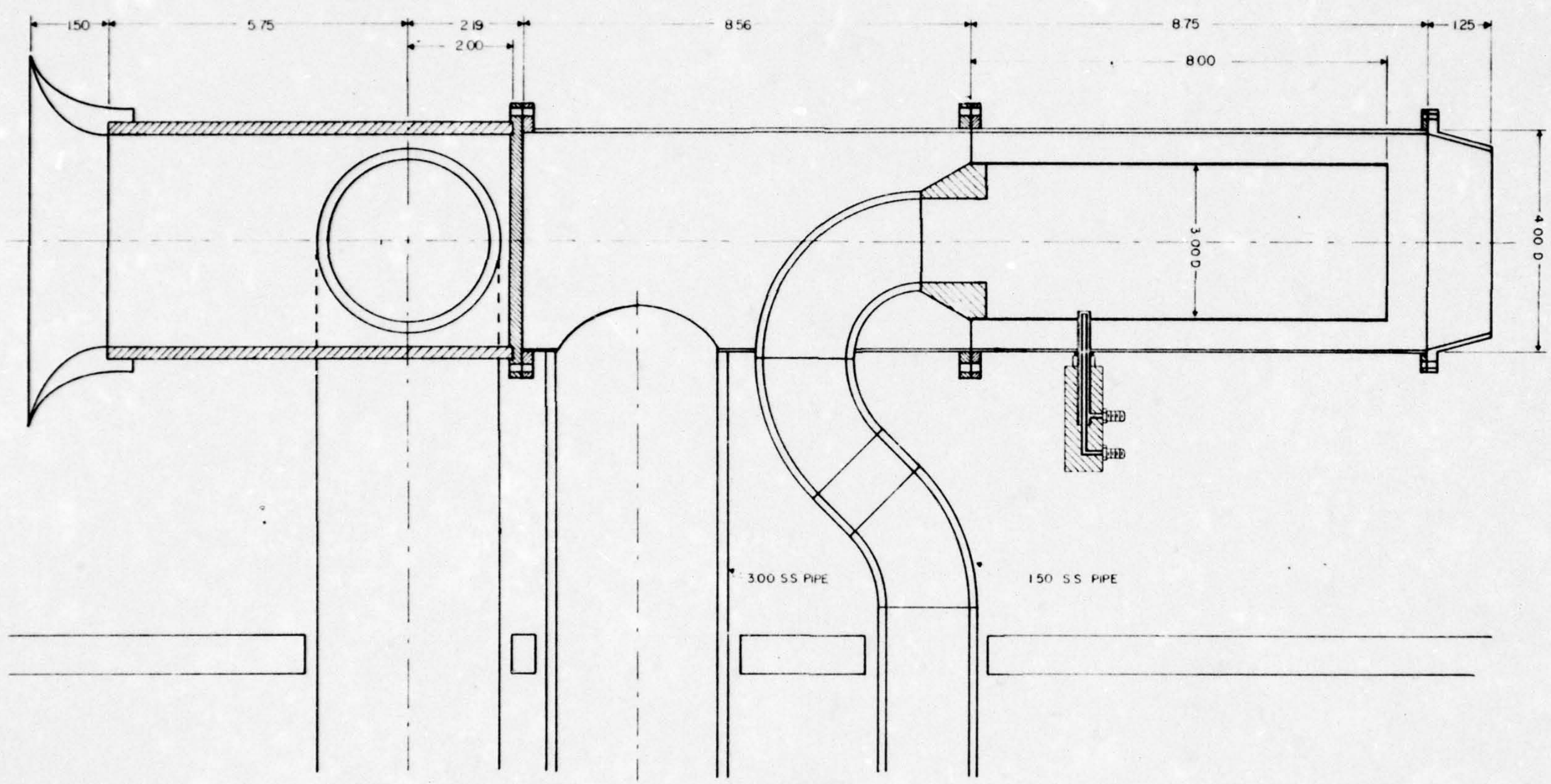


FIGURE 3. SCHEMATIC DIAGRAM OF RAMJET ENGINE

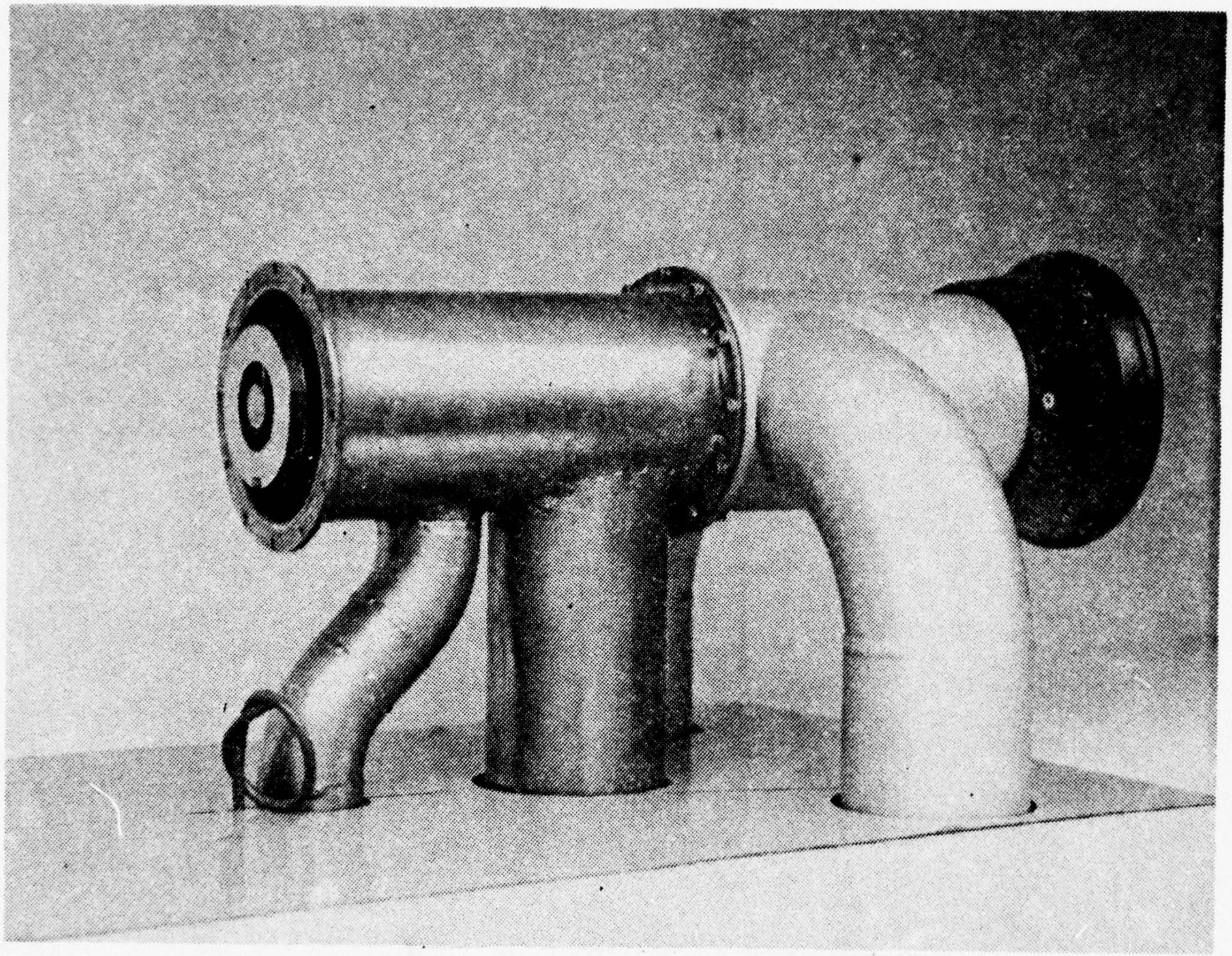


FIGURE 4. PHOTO OF RAMJET WITHOUT COMBUSTOR CAN (CENTER BODY LATER REMOVED)

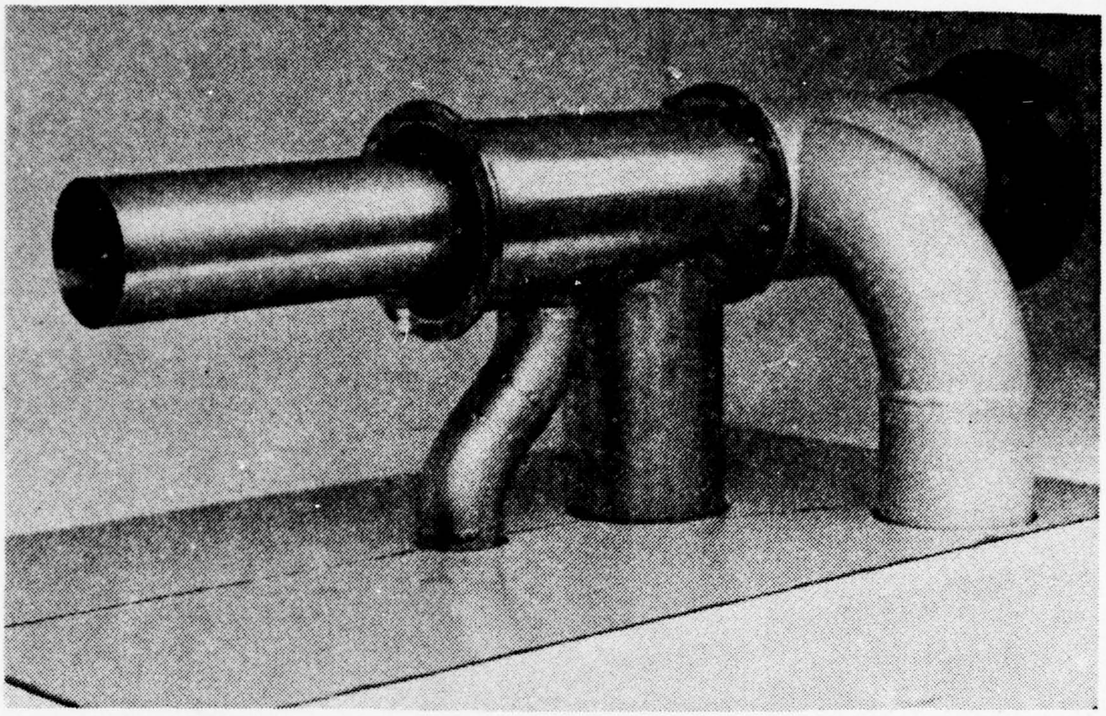


FIGURE 5. PHOTO OF RAMJET WITHOUT COOLING AIR JACKET

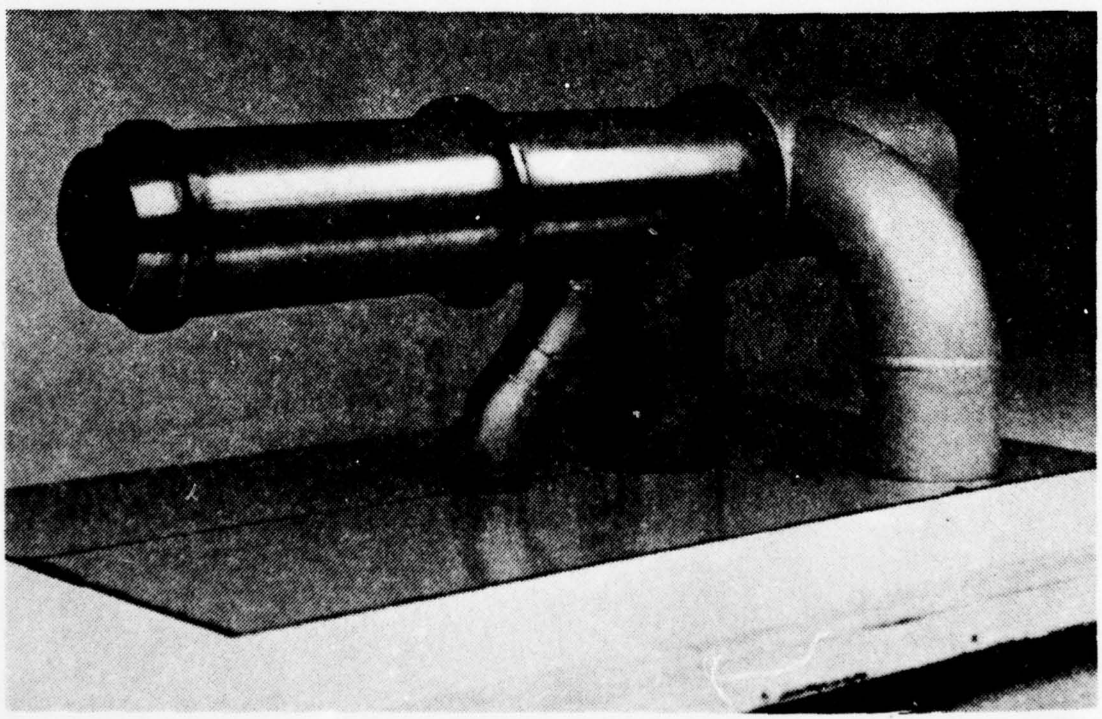


FIGURE 6. PHOTO OF RAMJET ASSEMBLY

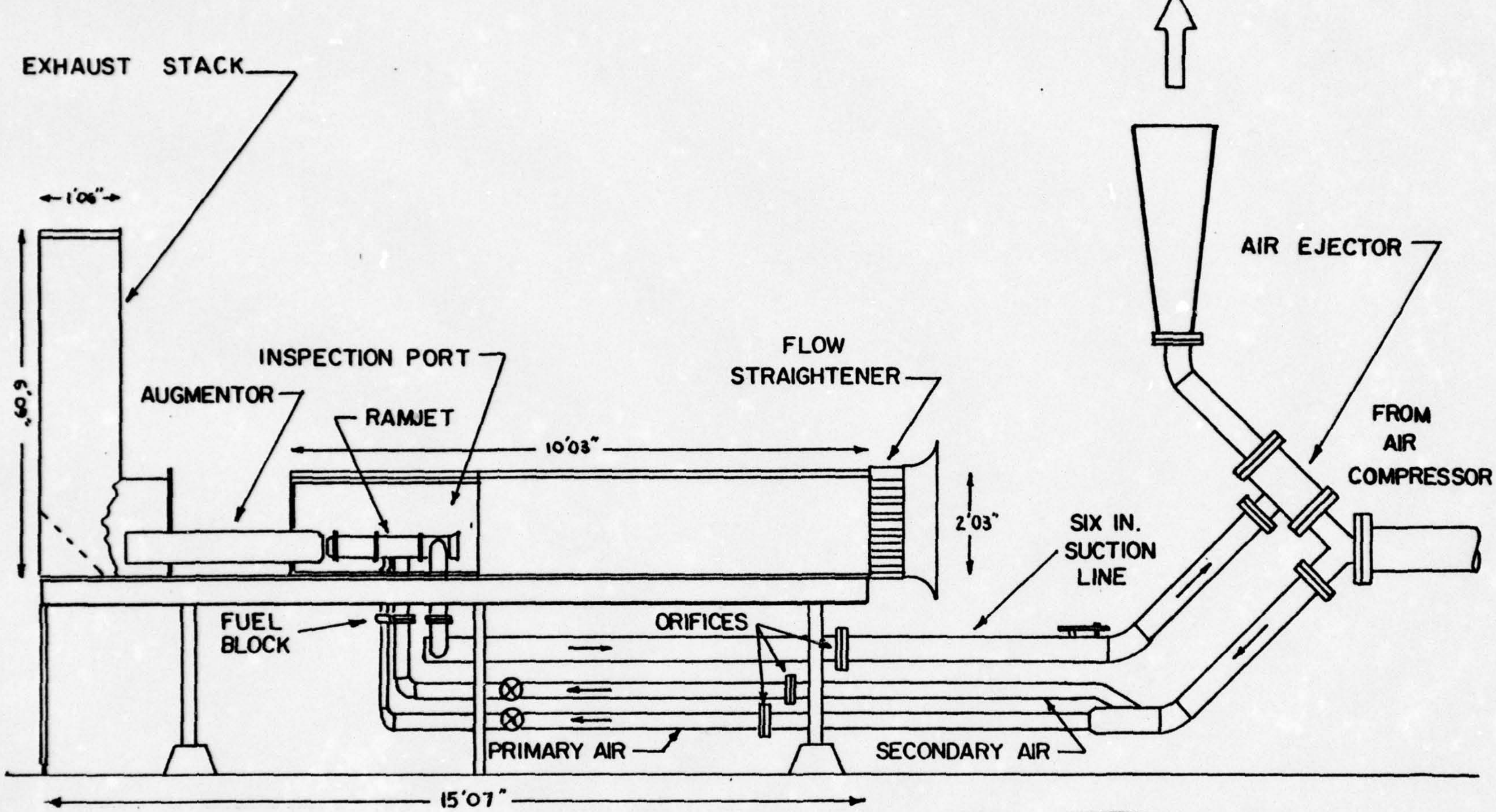


FIGURE 7. SKETCH OF 1/8 SCALE TURBOJET TEST CELL AND PIPING ARRANGEMENT

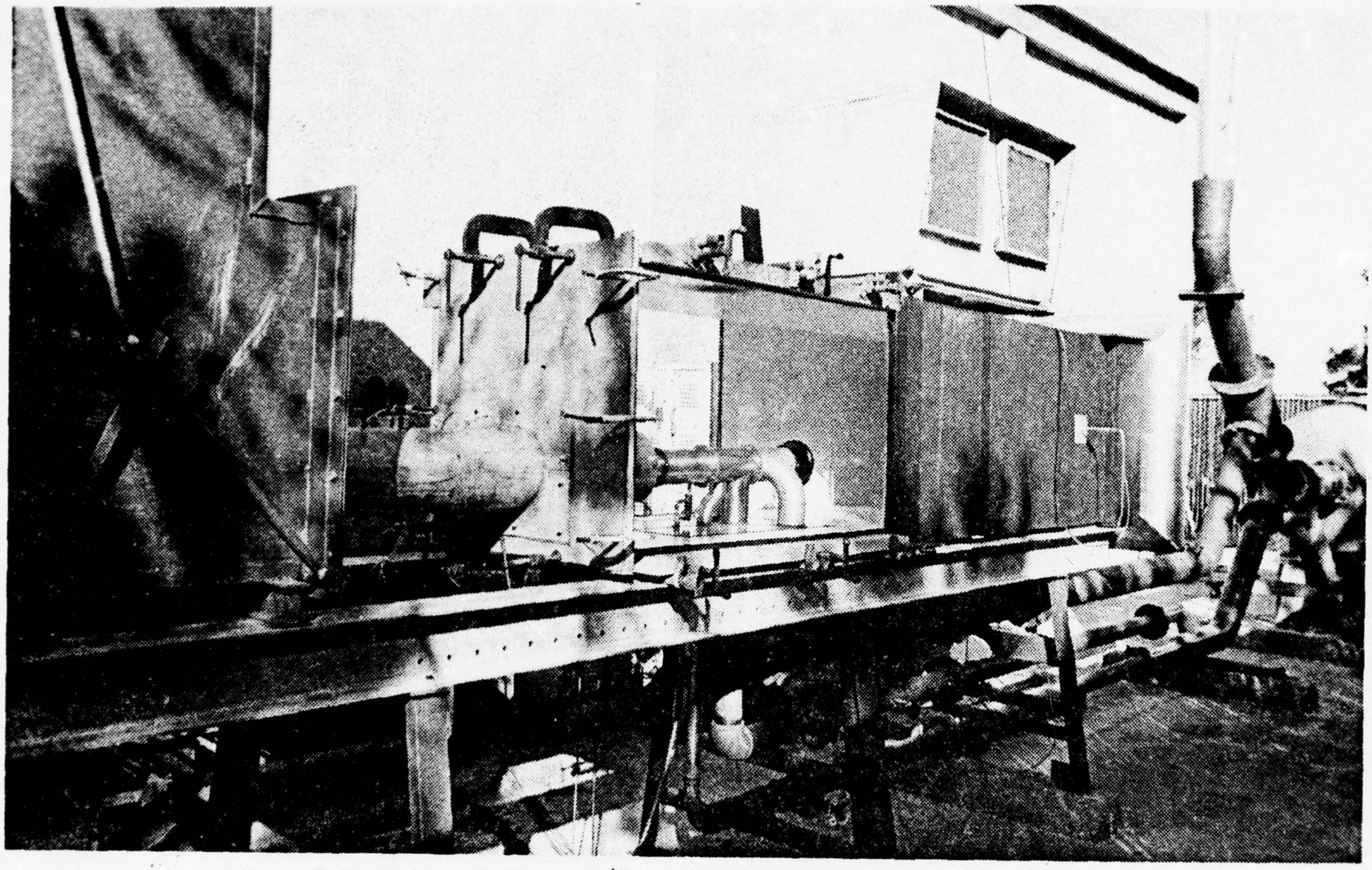


FIGURE 8. PHOTOGRAPH OF 1/8 SCALE TURBOJET TEST CELL FACILITY

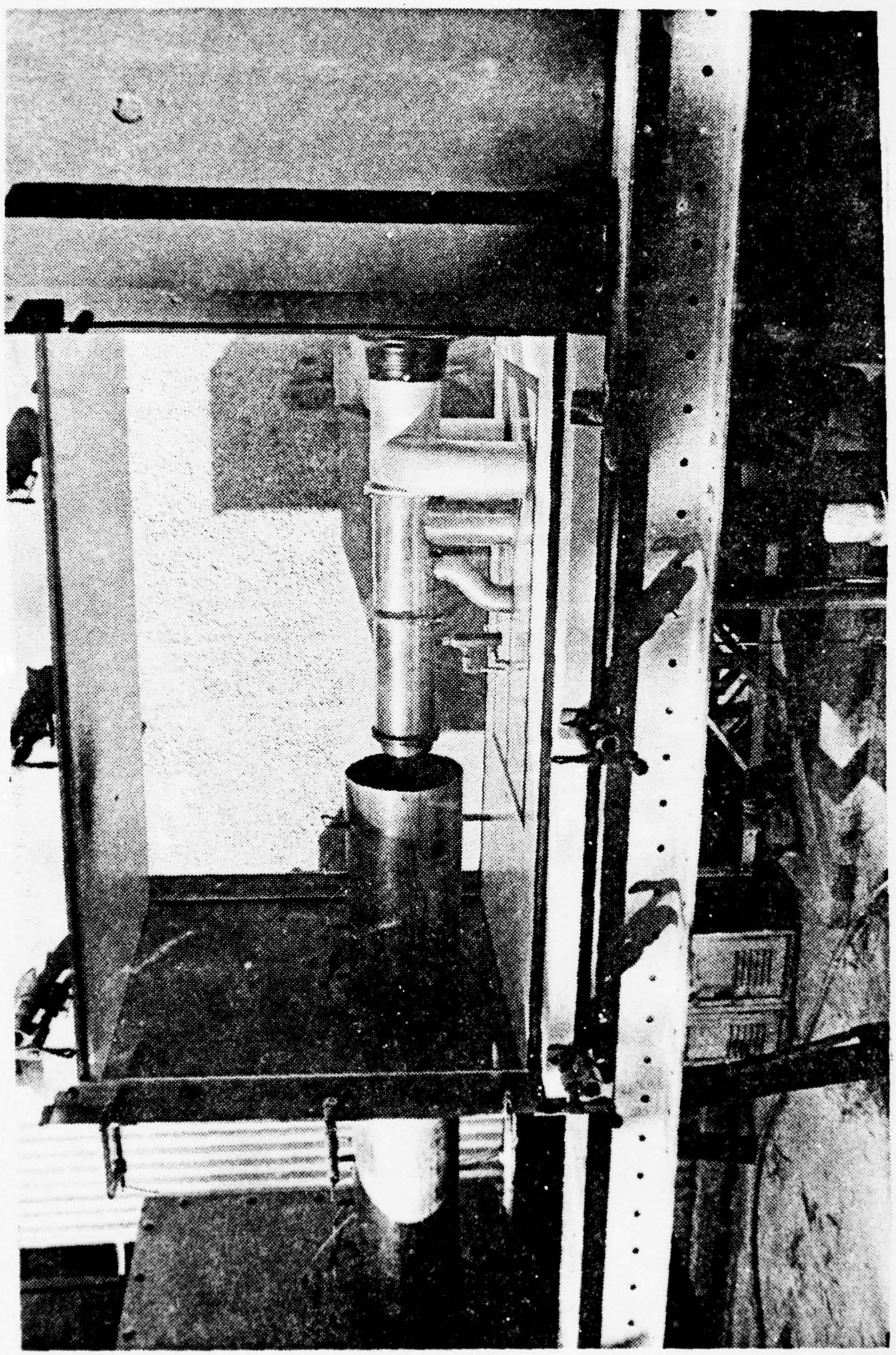


FIGURE 9. PHOTOGRAPH OF 1/8 SCALE TURBOJET TEST CELL FACILITY

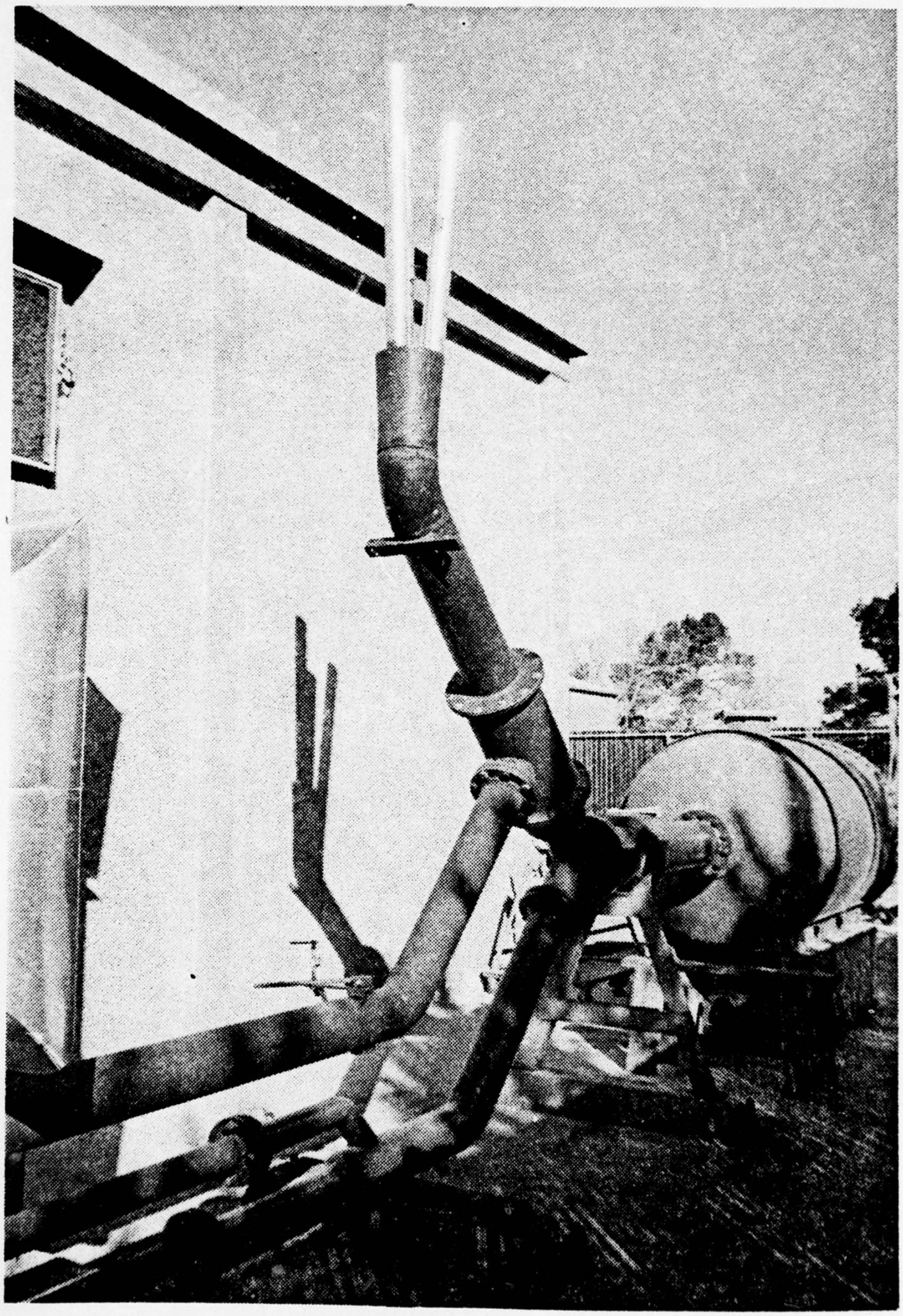


FIGURE 10. PHOTOGRAPH OF INTAKE AIR EJECTOR ARRANGEMENT

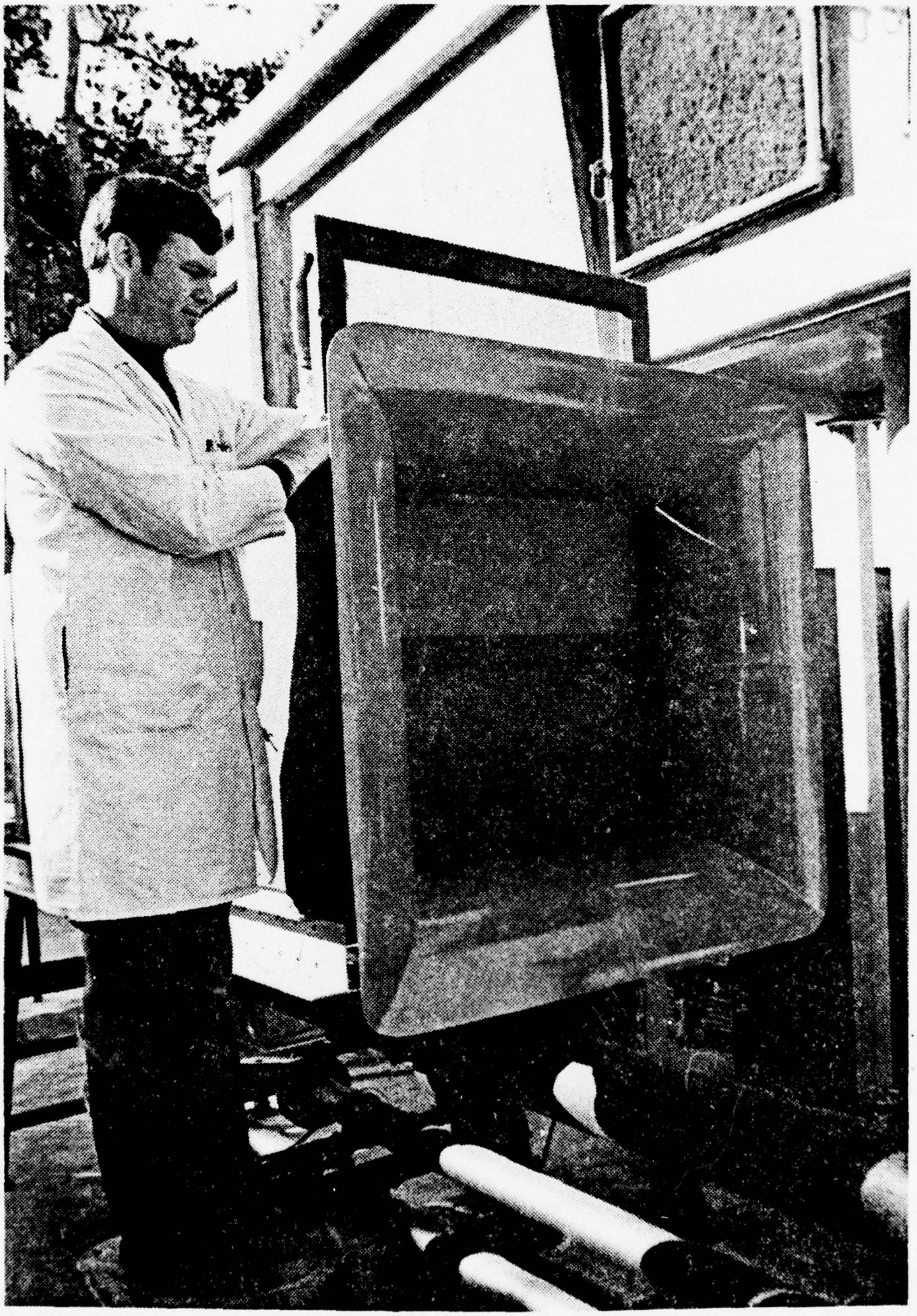


FIGURE 11. PHOTOGRAPH OF INLET FLOW STRAIGHTENER SECTION

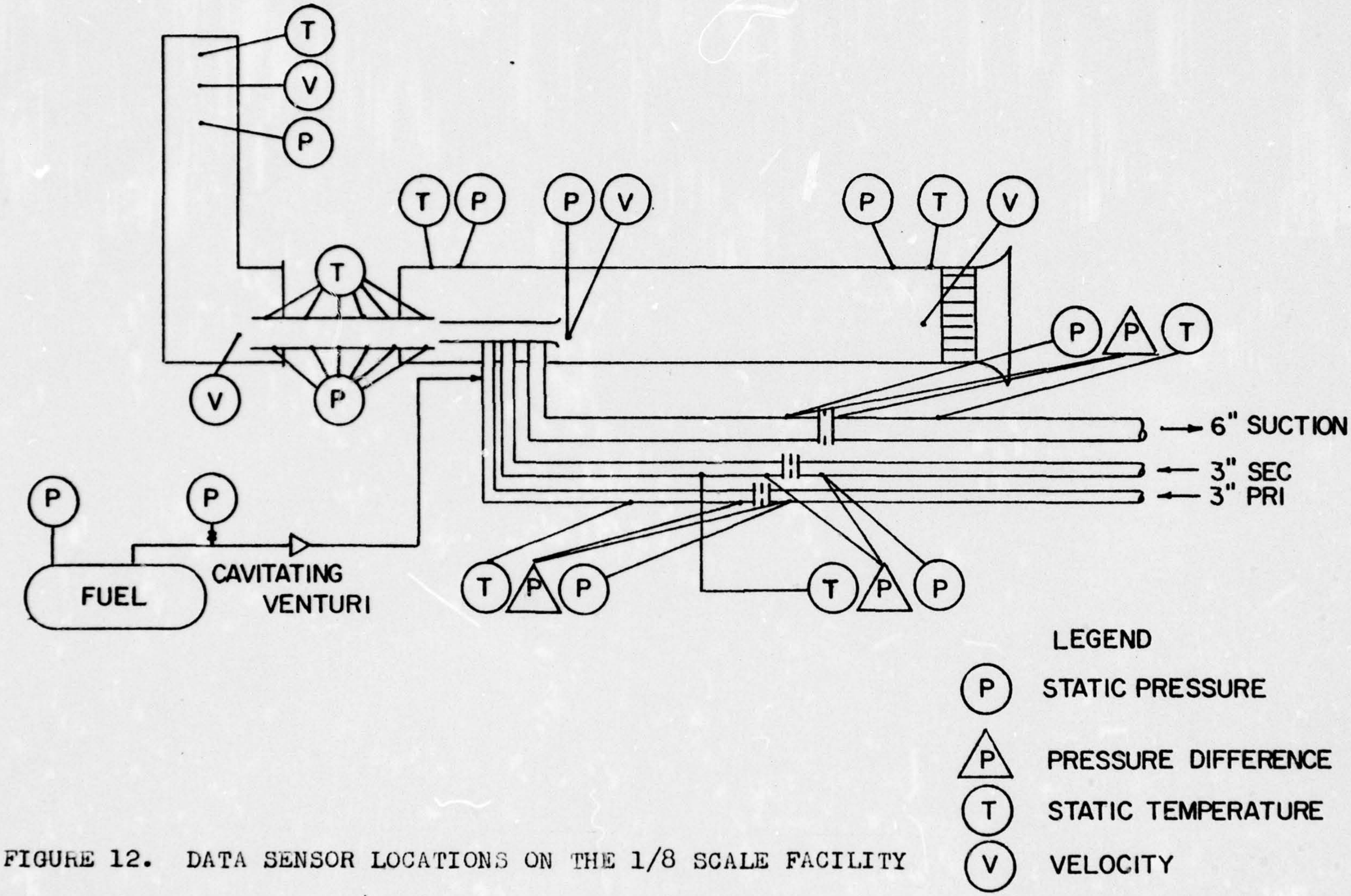


FIGURE 12. DATA SENSOR LOCATIONS ON THE 1/8 SCALE FACILITY

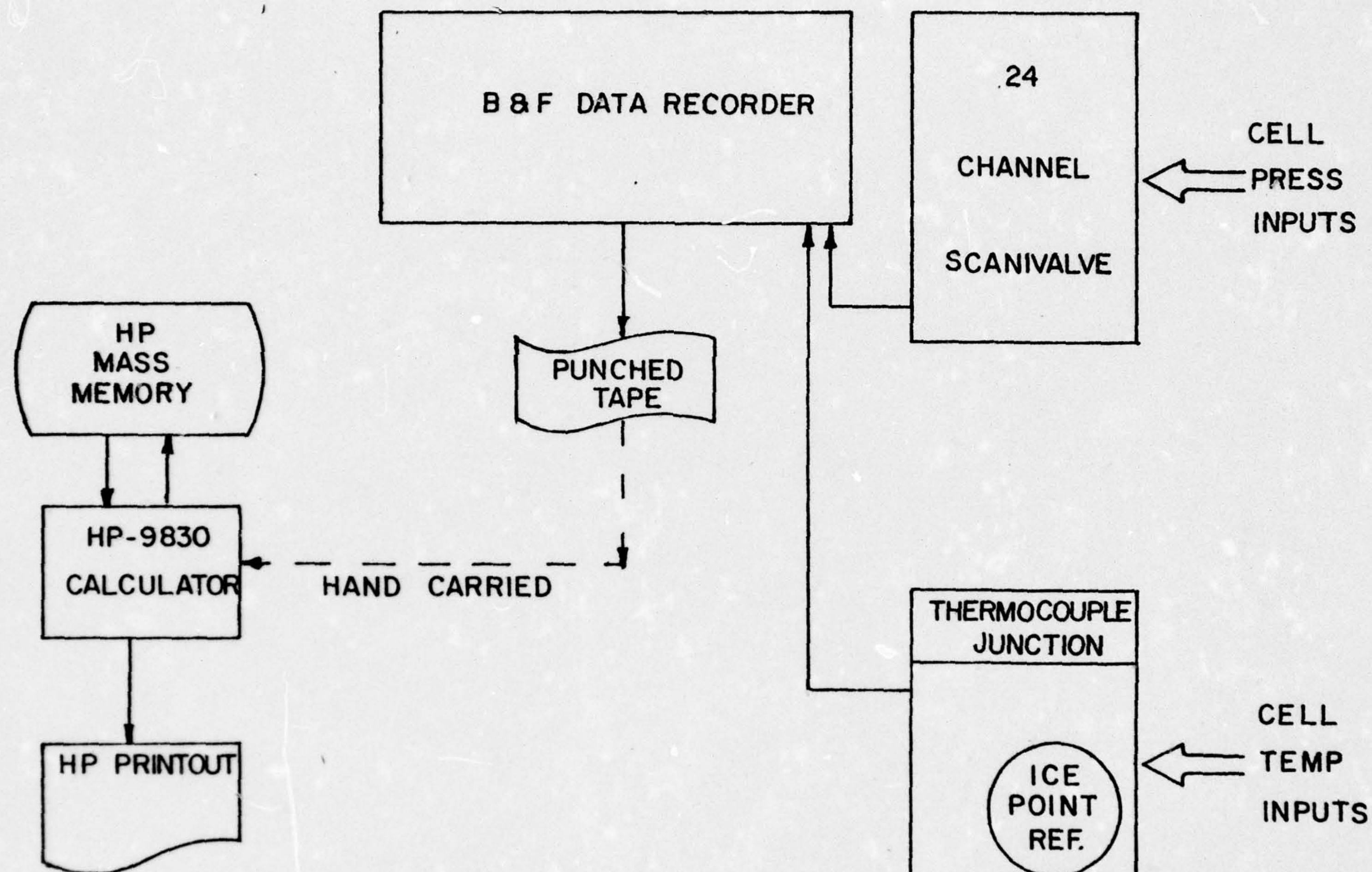


FIGURE 13. SCHEMATIC DIAGRAM OF DATA REDUCTION SYSTEM UTILIZING THE HEWLETT-PACKARD 9830A CALCULATOR.

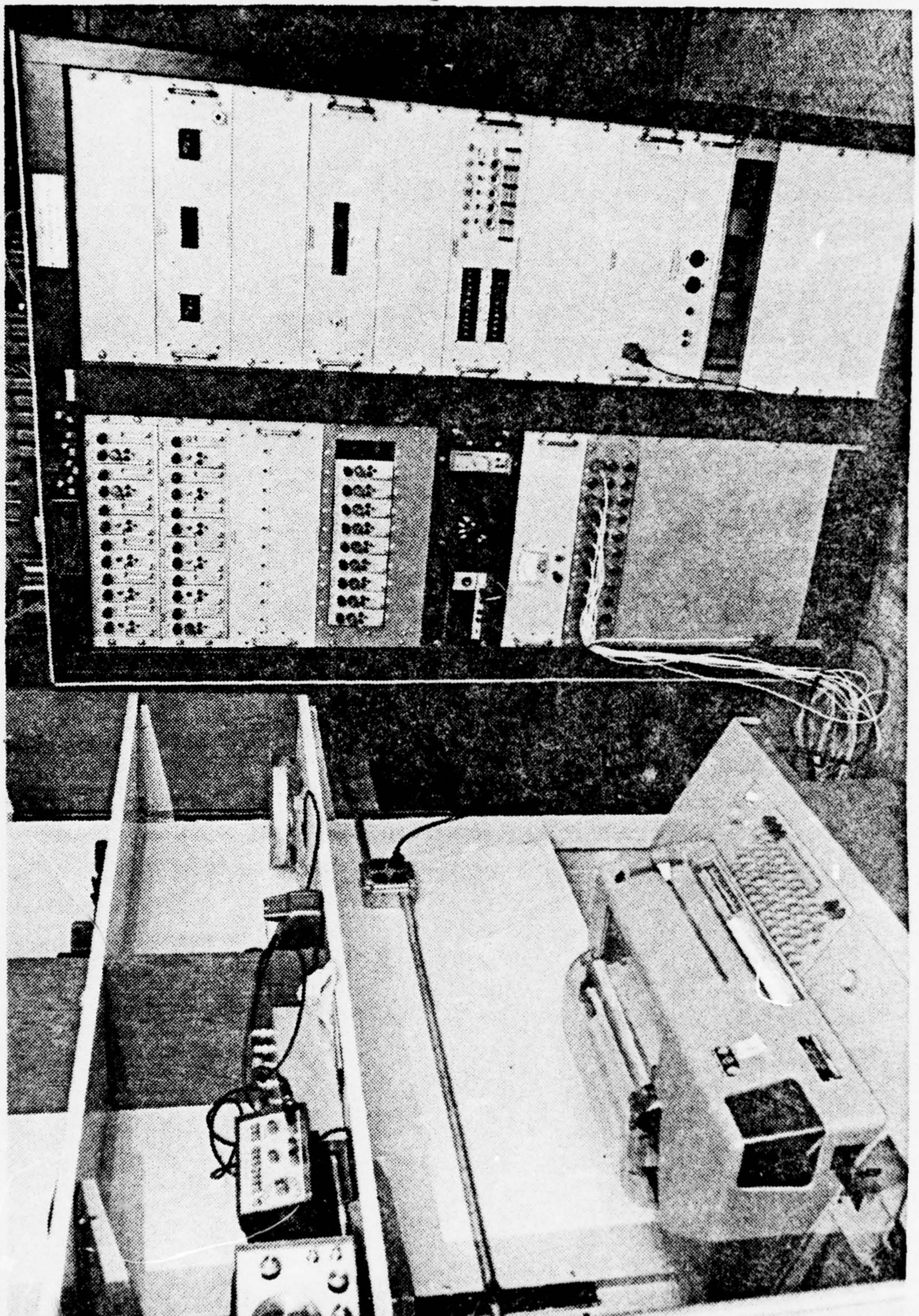
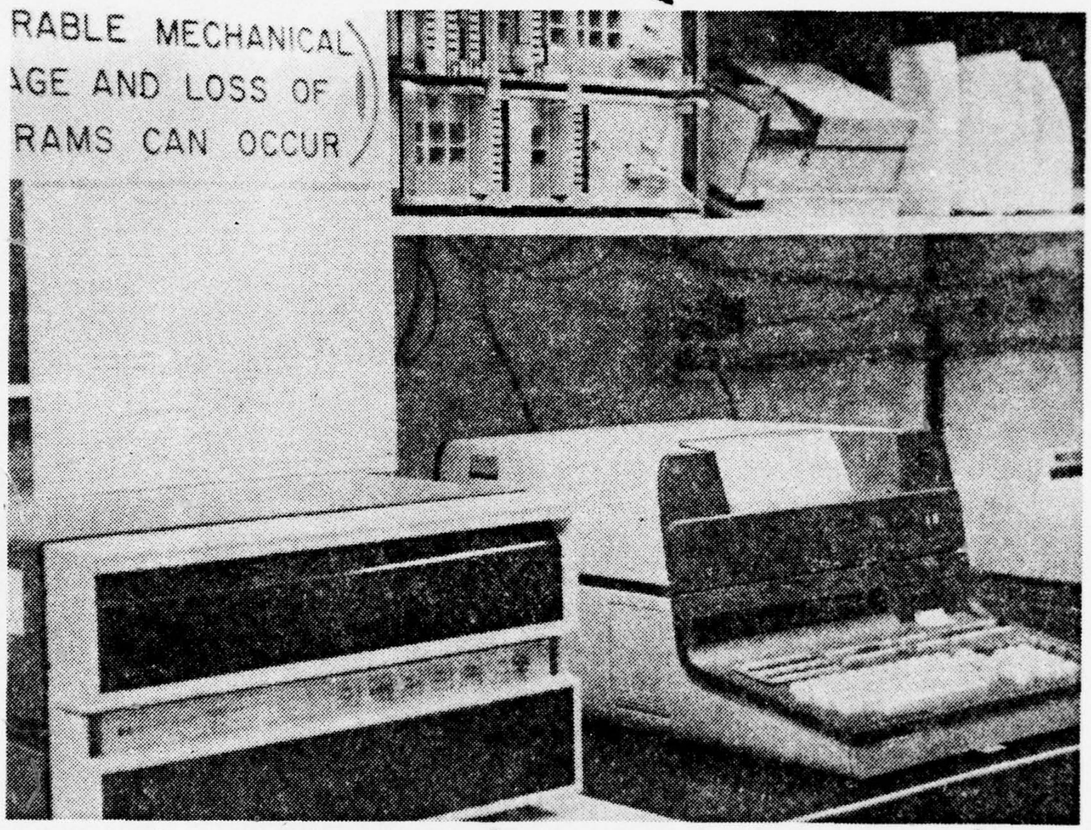


FIGURE 14. PHOTO OF B&F SY133 DATA LOGGER AND AN/UGC-59A TELETYPE MACHINE

TAPE READER



HP9867B MASS MEMORY UNIT

HP9830A CALCULATOR

FIGURE 15. HP9830 DATA REDUCTION CENTER

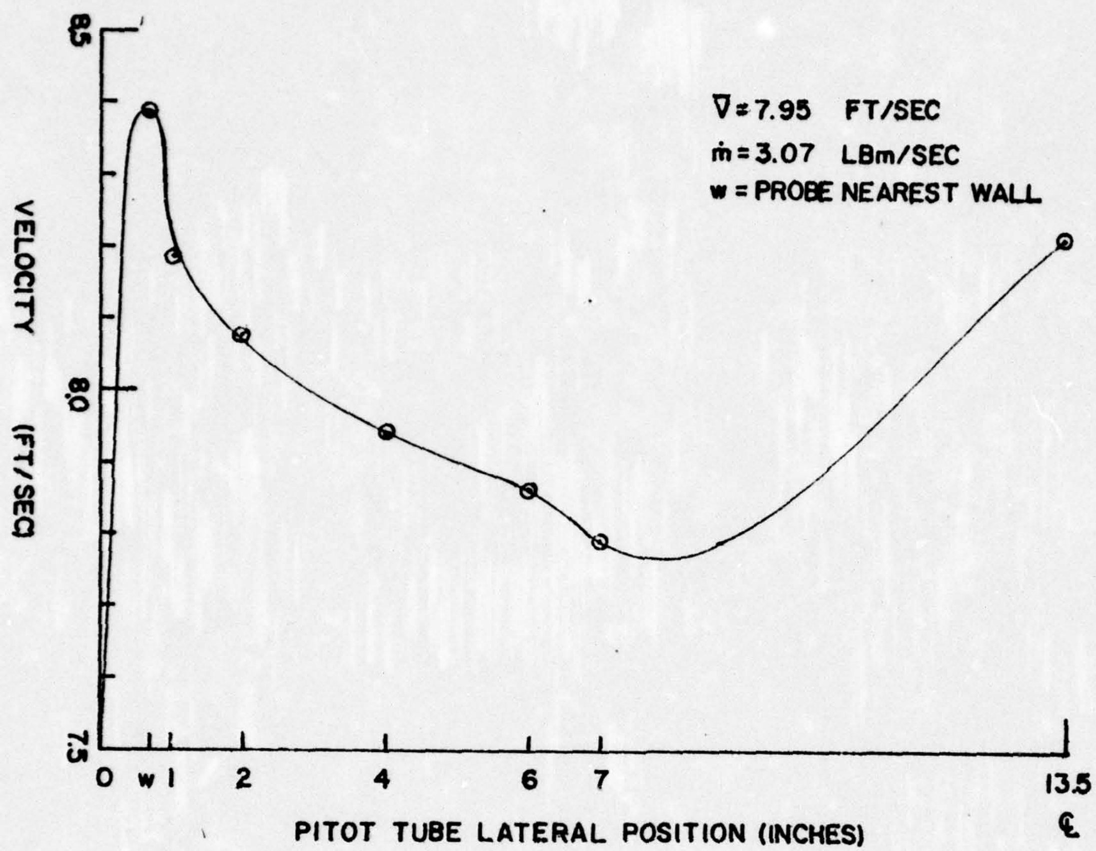


FIGURE 16. TYPICAL INLET VELOCITY PROFILE OBTAINED WITH A MICROMANOMETER

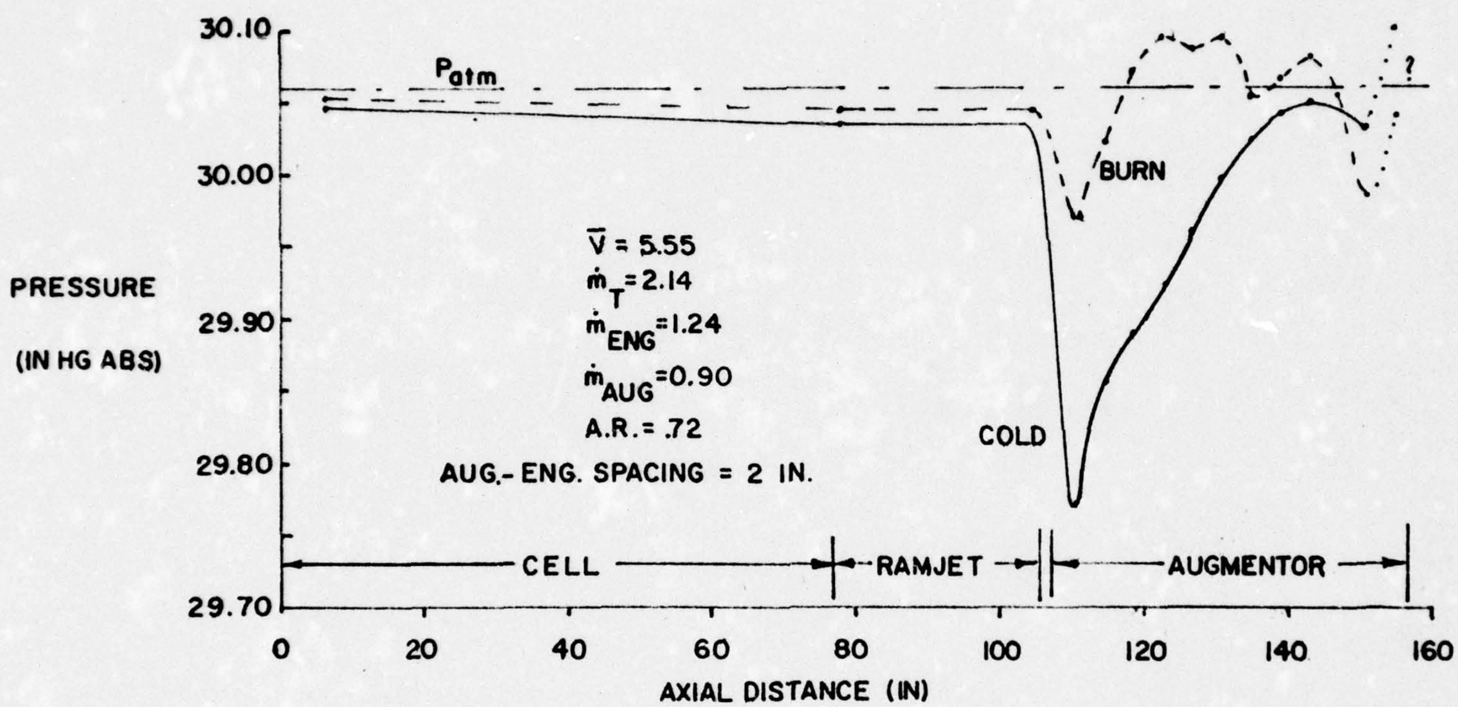


FIGURE 17. PRESSURE VS. AXIAL DISTANCE (ENGINE IDLE CONDITION)

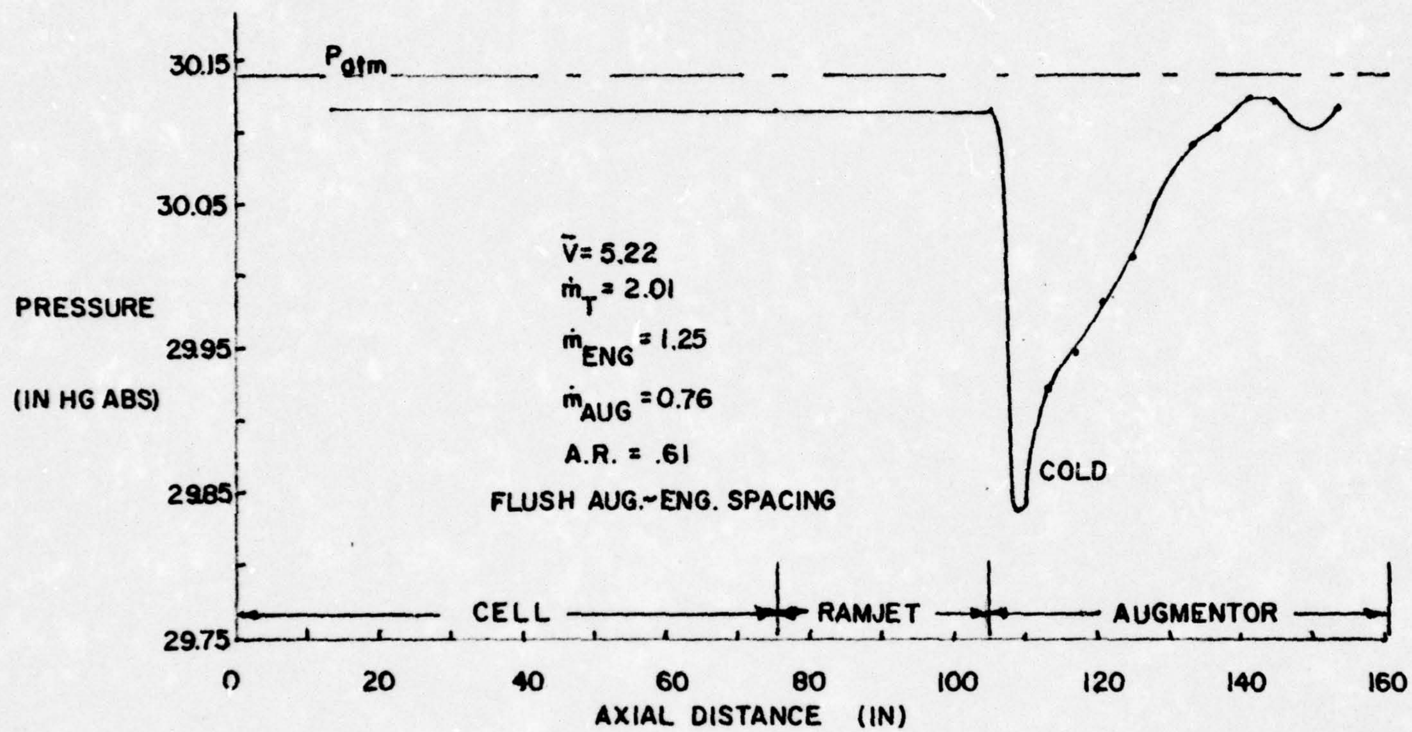


FIGURE 18. PRESSURE VS. AXIAL DISTANCE (ENGINE IDLE CONDITION)

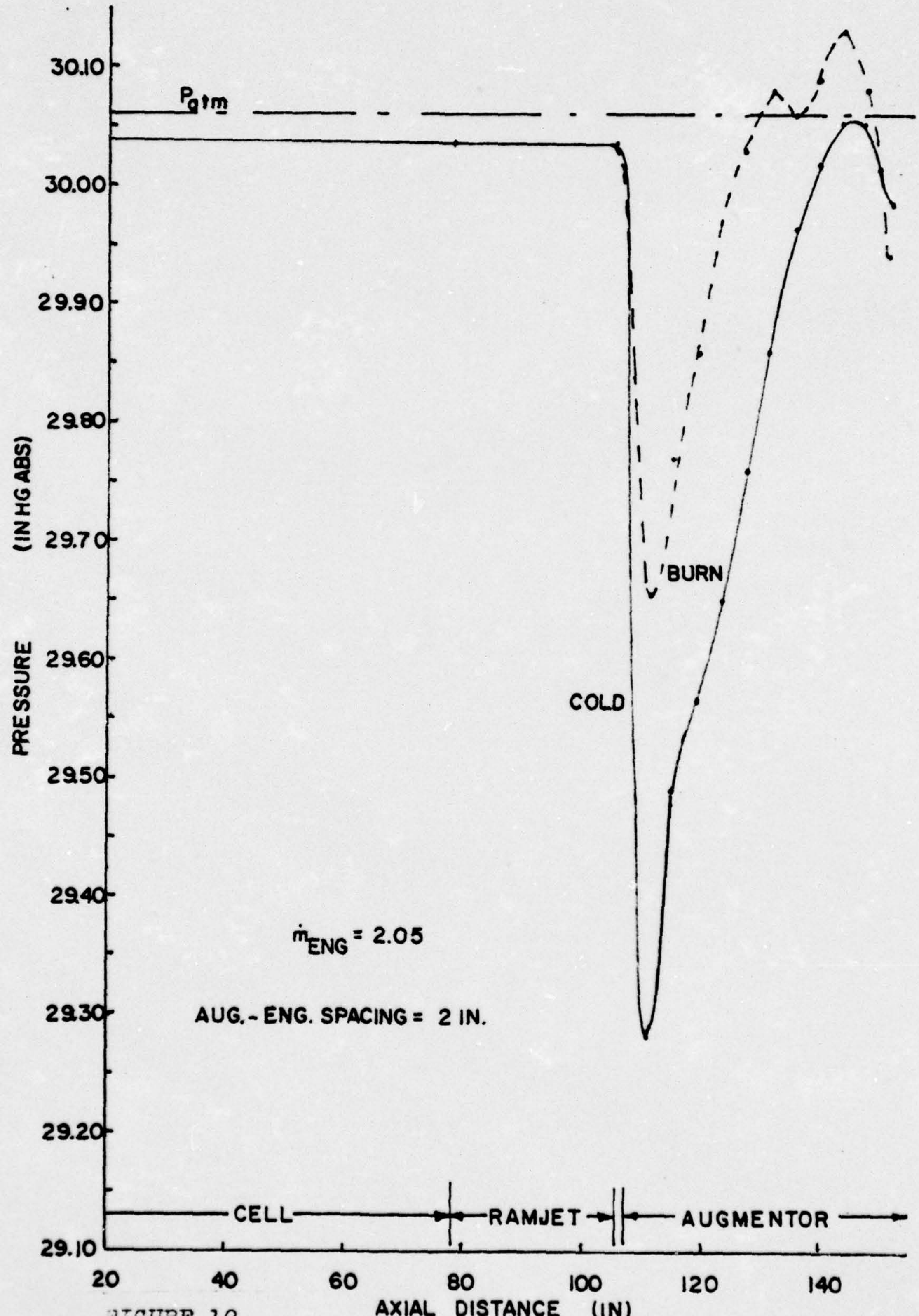


FIGURE 19.

PRESSURE VS. AXIAL DISTANCE (ENGINE 50% THRUST CONDITION)

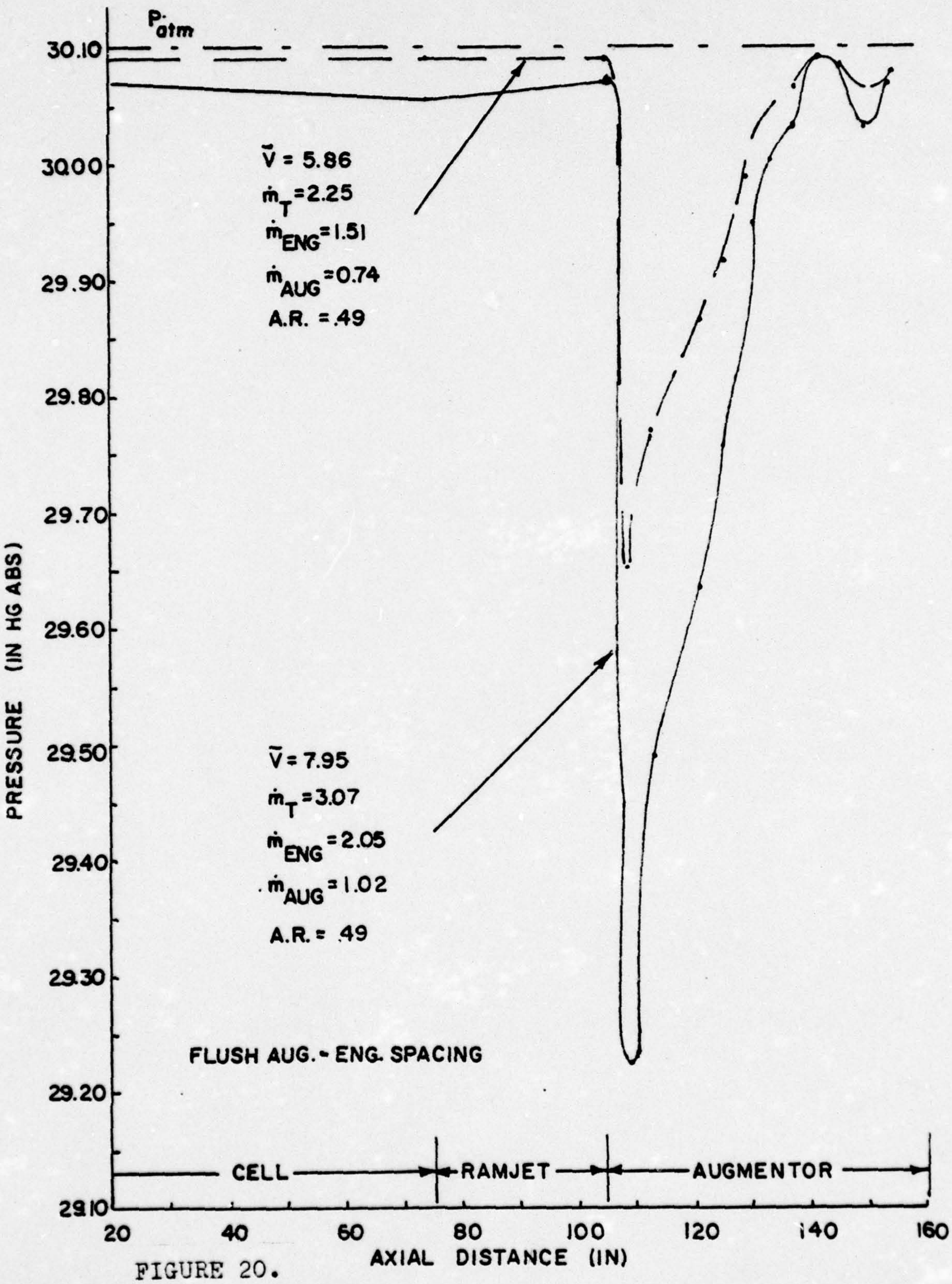


FIGURE 20.

PRESSURE VS. AXIAL DISTANCE (ENGINE MID-THRUST & 50% THRUST)

APPENDIX A: FUEL SYSTEM CALIBRATION

A1. APPARATUS

The fuel used in the combustion process of the ramjet engine was chosen to be JP-4 jet fuel to further simulate the operation of a turbojet/turbofan engine. JP-4 was adequately available from a number of nearby aviation facilities.

The system consisted of a pressurized fuel tank (Fig. A1) converted from an air compressor tank (water tested to 325 psig), a regulated nitrogen pressure source, a filter, a hand shut-off valve, an electrically operated solenoid rapid shut-off valve operated from the fuel control panel (Fig. A2), a cavitating venturi, and a fuel spray ring installed in the engine supply air line.

The purpose of the cavitating venturi was to provide fuel flow to the engine as a function only of upstream pressure. Downstream pressure fluctuations do not affect flow rate as long as the venturi is cavitating.

A2. METHOD OF CALIBRATION

There were two separate cavitating venturi used in the operation of the system, one for the higher flow rates and one for the lower flow rates. They had throat diameters of 0.046 and 0.032 inches respectively. Flow rates as a

function of upstream pressure for the two venturis are presented in Figure A3.

In order to calibrate the venturis, the fuel tank was pressurized to pre-set values within the desired flow range. At each pressure setting, the flow of JP-4 fuel was collected in a container placed on a balance scale. The time required for each pound-mass increment was recorded with a Hewlett-Packard HP-55 hand-held calculator. The flow rate of the fuel was then computed by the equation

$$\dot{m}_{fuel} = \frac{\Delta wt.}{\Delta t} \qquad A(1)$$

The flow rate was then plotted as a function of fuel tank pressure (Fig. A3).

In addition to the tank pressure measurement during the calibration testing, it was desired to know the maximum back pressure where the venturi would no longer cavitate. This was determined by installing a valve and pressure gauge on the downstream side of the venturi and increasing the back pressure during the flow measurement until the flow rate decreased. That pressure was additionally recorded and plotted in Figure A3 to show when the venturi plot was invalid as a fuel flow reference.

The pressure-flow rate plot was used in the operation of the turbojet test cell to determine the fuel flow rate once the air flow rate into the combustor

can was established as detailed in Appendix B and once a fuel/air ratio was selected by the operators.

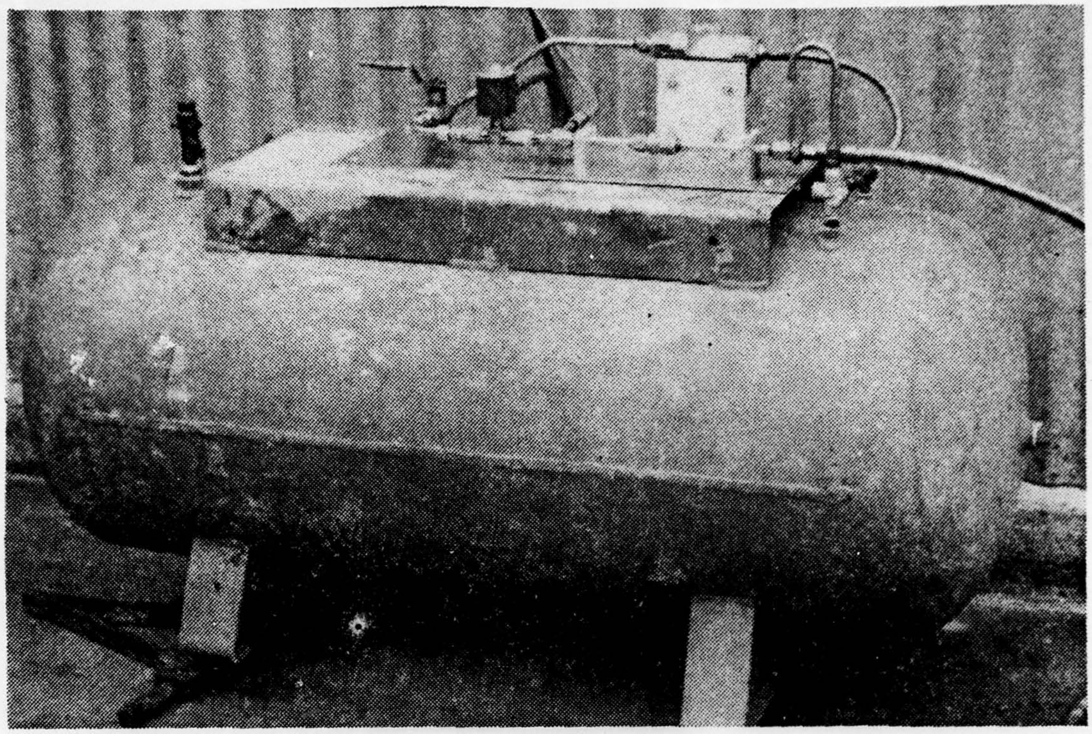


FIGURE A1. PRESSURIZED JP-4 FUEL TANK

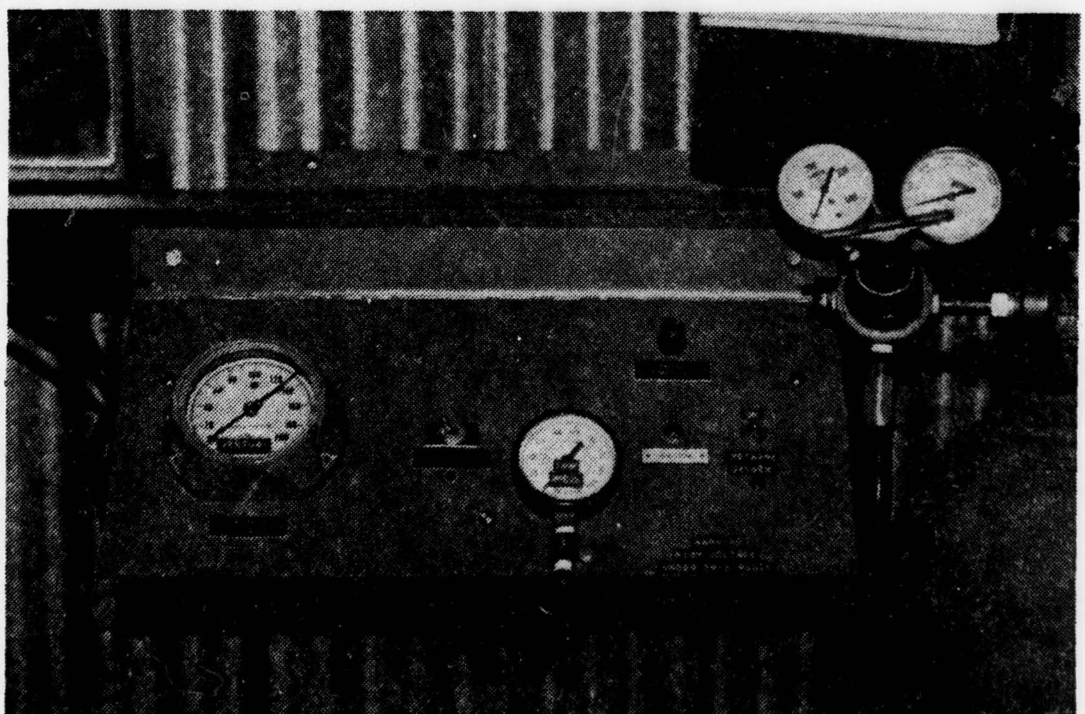


FIGURE A2. FUEL CONTROL PANEL

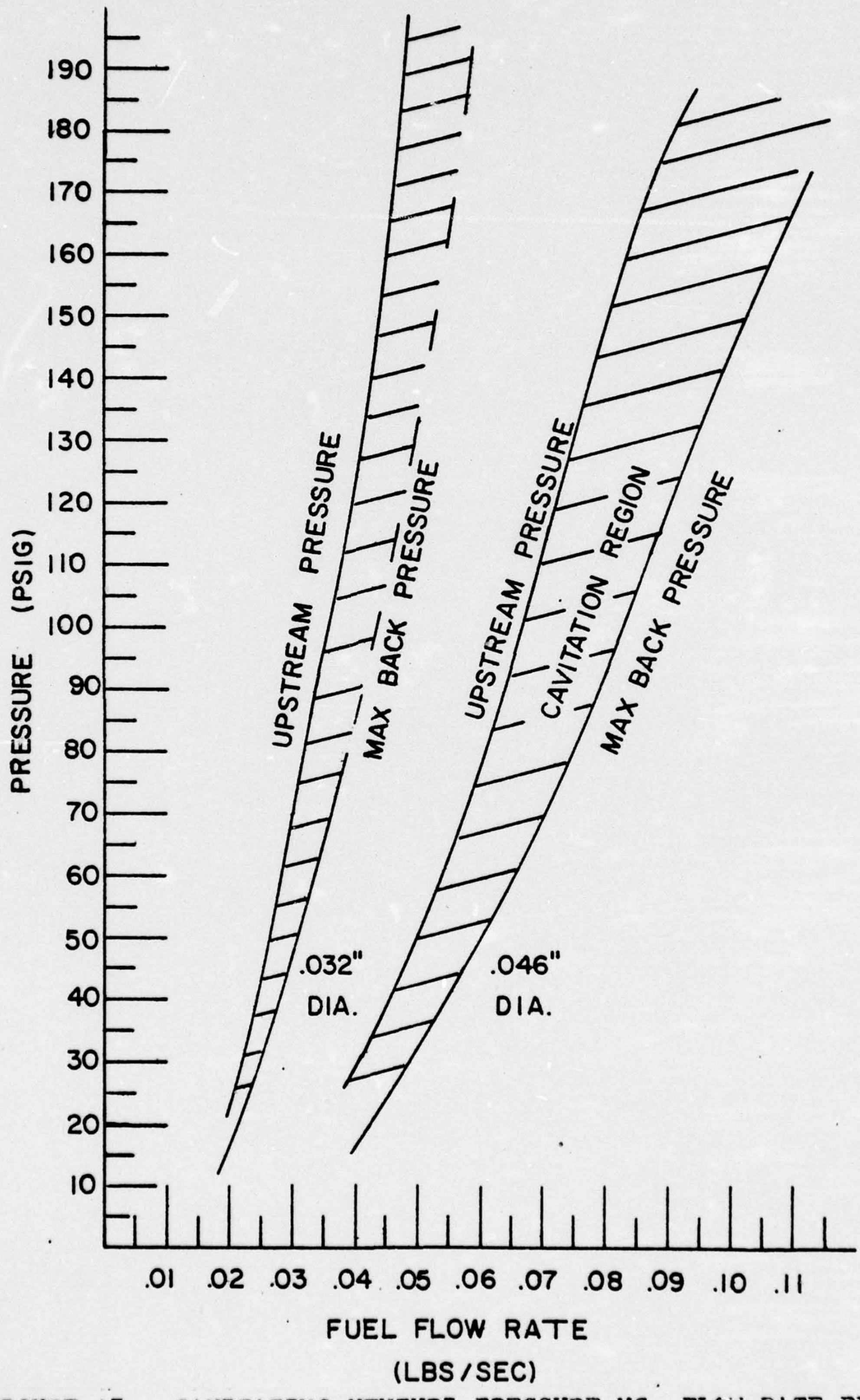


FIGURE A3. CAVITATING VENTURI PRESSURE VS. FLOW RATE PLOT

APPENDIX B. DATA REDUCTION

B1. INTRODUCTION

Air flow rate measurement through a duct can be measured using a standard A.S.M.E. orifice (Ref. 5) This requires the use of a semi-empirical equation which requires the input of the upstream static pressure, the drop in pressure across a prescribed this plate orifice and the downstream static temperature. The calculation of the flow rate by the A.S.M.E. procedure is a time consuming process since it involves a number of empirical coefficients based on temperature, pressure and construction technique.

The temperature and pressure data collected for determining the flow rates to the one-eighth scale turbojet test cell were all recorded in both raw data and reduced data form in the mass memory storage unit after processing by the pre-programmed HP9830A Calculator.

The calculated flow rates for the ramjet engine components were used for two purposes:

a) Storage for later analysis

b) Determination for real-time decisions regarding the desired flow rate balancing of the ramjet.

B2. AIR FLOW RATE CALCULATION

The flow of air through an orifice is calculated with

the equation

$$\dot{w}_h = 359\ CFd^2 F_a Y \sqrt{h_w / v_1} \qquad B(1)$$

where $\dot{w}_h$ is the air flow rate in pounds-mass per hour, C is the coefficient of discharge, F is the velocity of approach factor, d is the diameter of the orifice in inches, F_a accounts for the thermal expansion of the orifice, Y is the net expansion factor for square-edged orifices, h_w is the effective differential head in inches of water, and v_1 is the specific volume of the air at the inlet side of the orifice in cubic feet per pound-mass. The factors C and F may be combined into a single flow coefficient, K which is tabulated in Reference 5 as a function of the pipe Reynolds number, R_D and diameter ratio, β. β is the orifice diameter, d, divided by the pipe diameter, D. The factor 359 in equation B(1) is a constant that converts the various units to those commonly used in American practice.

The flow rate calculations performed in the sub-scale test cell data reduction program used equation B(1) with certain variable and unit modifications for easier identification and utilization. The equation adapted was

$$\dot{w} = 0.11482\ d^2 aKY \sqrt{p \Delta h / T_a} \qquad B(2)$$

where $\dot{w}$ is now air flow rate in pounds-mass per second, d is the orifice diameter, a is the thermal expansion factor K (=CF) and Y are the same as in equation B(1), p is the static pressure upstream of the orifice in inches of

mercury absolute, Δh is the pressure drop across the orifice in inches of water absolute and T_a is the temperature of the flowing air downstream of the orifice in degrees Rankine.

The following procedure was followed for one iteration of the flow rate calculation:

a) a = 1.0005 which is essentially a constant for the near ambient air conditions encountered in the test facility and an orifice of stainless steel.

b) $\beta = d/_D$ B(3)

c) $Y = 1-.05246\ (.41 + .35^4)\Delta h/p$ B(4)

d) The fluid viscosity as a function of temperature, was estimated using a polynomial developed from the tables in Reference 5

$$\mu = 1.0916678\times10^5 + 1.85811\times10^{-8}(T)-6.946\times10^{-12}(T)^2 \qquad B(5)$$

where T is in degrees Fahrenheit and μ is in pounds-mass per foot-second.

e) Reynolds number was calculated as a function of flow rate, pipe diameter and viscosity by

$$R = \frac{48\ \dot{w}}{\pi D \mu} \qquad B(6)$$

where initially a flow rate is assumed.

f) K, the flow coefficient is then determined as a function of β and Reynolds number, R. Various polynomials were developed from tabulated data in Reference 5.

For example, the three-inch primary air supply

line had a diameter of 3.068 inches and an orifice diameter of 2.149 inches. Thus, β = 0.7 and

$$K = 0.710655-.000297\ (R/.0001)-.000002(R/.0001)^2 \qquad B(7)$$

g) The flow rate is calculated using equation B(2)

$$w = 0.11482\ d^2 aKY\sqrt{p\Delta h/T_a} \qquad B(8)$$

The iterative process is repeated by substituting $\dot{w}$ back into equation B(6) and continuing through again as in steps e, f and g until the difference between the flow rate of equation B(8) and the flow rate used in equation B(6) is nearly zero (i.e. less than 10^{-5}).

The above procedure was carried out for the flow rate calculations in the three-inch primary air supply line, the three-inch secondary air supply line and the six-inch intake suction line each time the data reduction program was utilized.

B3. PROGRAM FOR RAW DATA ACQUISITION AND STORAGE

B3.1 Description. Program "HEW1" (TABLE B2) was written for the Hewlett-Packard 9830A Calculator to read the paper tape punched by the teletype machine which in turn was coupled to the B&F data logger (Figs. 13 and 14). The B&F data logger provided A/D conversion for the 24 channels of pressure data acquired by the scanivalve and the various temperatures. The program arranged the raw data in a matrix format and produced a printout of the matrix with a heading indicating the run number, point number,

date of the run and the title of the project. Additionally, the program was written to store the matrix for later use in reduction and contained a feature to allow for corrections to the raw data matrix if desired.

B3.2 Operation. Detailed information on the operating procedures for the HP-9830A Calculator, mass memory and assorted equipment are found in References 7 and 8. The following is a step-by-step procedure for the program called "HEW1".

1. After loading "HEW1" into the Hewlett-Packard 9830A Calculator press "RUN" and "EXECUTE".

2. The calculator will then display "AUTO STORAGE? YES=1, NO=0". If yes is the desired input, the program will proceed to step 3. If no is replied, the calculator will order "ENTER NEXT RECORD # ON DATA FILE".

3. The calculator next displays "ENTER FIRST RECORD # THIS RUN" which requires the number of the record desired for the storage of the present data in matrix format.

4. The calculator now querries "TAPE: 1ST HOLE?-ON START?: CONT." which means for the operator to line up the punch tape in the tape reader and then press "CONT" and "EXECUTE".

5. Following a brief pause after running the paper tape through the tape reader, the calculator will flash on "CORRECTIONS TO DATA? - YES=1, NO=0". A no response will take the calculator to step 6. A yes response will invoke a display "PRESS PRTALL KEY FOR RECORD." and "ENTER

CORRECTION AS MATRIX ELEMENT". When these instructions are carried out the calculator will display "ENTER CORRECT VALUE?; EXEC., CONT., EXEC." which allows the operator to manually make corrections by entering the corrected data in its proper place via keyboard typewriter. Then "CONTINUE" is keyed which displays "ANY MORE CORRECTIONS? YES=1, NO=0," which is self explanatory.

6. The calculator prints out the raw data file.

7. Next, the calculator asks "STORE DATA? ENTER YES=1, NO=0." If a yes is given the calculator stores the matrix in the appropriate raw data file. If no, the calculator prints "THIS DATA WAS NOT STORED" and sends the program back to step 2.

8. After the raw data is stored, the program returns to step 2 for the next automatically updated file number. The operator may opt to "STOP" or simply "GET" another program.

B4. PROGRAM FOR RAW DATA REDUCTION AND REDUCED DATA PRINT-OUT AND STORAGE.

B4.1 Description. Program "HEW2" (TABLE B3) was written for the HP-9830 to call out the raw data matrix stored by program "HEW1" for processing into usable data for the operator to analyze and store for later analysis or publication.

"HEW2" was also the only source of usable air flow rate data used for real time decisions of line flow balance, air/fuel ratio and system operation.

B4.2 Operation. The following is a step-by-step operating procedure for the program "HEW2".

1. After loading "HEW2" into the HP-9830A Calculator press "RUN" and "EXECUTE".

2. The calculator then displays "ENTER RECORD # THIS POINT" which must correspond to the record # stored in program "HEW1".

3. Next, the calculator displays "BAROMETRIC PRESS(INHG)=." The operator then types in the local pressure which is used to correct the pressure inputs from gauge to absolute pressure.

4. The calculator will then provide the operator with a printout of the reduced data and also display "STORE DATA? ENTER YES=1, NO=0". If the operator responds no, the calculator prints "THIS DATA HAS NOT BEEN STORED" and returns to step 2. If the operator responds yes, the calculator prints "THE REDUCED DATA IS STORED IN TJRED1 RECORD #__." The process will then stop and will not resume unless the operator returns to step 1 or "GET"s a new program.

TABLE B1

RECORD OF VARIABLES USED

	ARRAY		0	1	2	3 (3" PRI)	4 (3" SEC)	5	6 (6" SUC)	7	8	9
A	MATRIX					a	a		a			
B			LOCAL BARO.			β	β		β			
C	MATRIX											
D						PIPE DIA	PIPE DIA		PIPE DIA.			
E		fn			fn							
F		fn			fn							
G		fn			fn							
H						Δh ORIFICE	Δh	PRESS	Δh DIFF.			
I												
J												
K												
L												
M						μ	μ		μ			
N												
O						ORIFICE DIA	ORF. DIA	ORF DIA.	ORF DIA.			
P	MATRIX					ρ UPSTREAM	ρ		ρ PRESS.			
Q												
R		fn	fn									
S		fn										
T						T ORIFICE	T	TEMPS	T			T_{REF}
U												
V												
W						$\dot{W}$ 3 PRI	$\dot{W}$ 3SEC		$\dot{W}$ 6 SUC			$\dot{W}$ INIT.
X												
Y						Y	Y		Y			
Z		MATRIX										

TABLE B2. PROGRAM "HEW1" RAW DATA PROCESSING

```
1 REM-----------*****HEW1*****------------------------------------------------
2 REM-----------DATA REDUCTION FOR 1/8 SCALE TURBOJET TEST CELL------------------
3 REM  PRINT "CHECK APPROPRIATE FILENAME, LINES 1210, 1270, CONTINUE 10"
10 DIM C$[56],A$[48]
11 DISP "AUTO STORAGE? YES=1, NO=0";
12 INPUT Z
13 IF Z=0 THEN 40
14 DISP "ENTER FIRST RECORD # THIS RUN";
15 INPUT E1
16 GOTO 70
40 DISP "ENTER NEXT RECORD # ON DATA FILE";
50 INPUT E1
70 M9T A=ZER
80 MAT C=ZER
90 DISP "TAPE:1ST HOLE?-ON START?:CONT."
100 STOP
110 REM-----------READ PAPER TAPE--------------------------------------------
120 ENTER (7,130)C[1],C[2],C[3],C[4],C[5]
130 FORMAT 1X,F2.0,1X,F2.0,1X,3F2.0
140 ENTER (7,150)I,J,K
150 FORMAT 2X,F3.0,1X,F2.0,1X,F6.0
160 IF I=3 THEN 200
170 IF 49<I AND I<57 THEN 220
190 GOTO 140
200 A[J]=K
210 GOTO 140
220 C[I]=K
225 IF I=56 THEN 260
230 GOTO 140
260 REM-----------DATA CORRECTIONS--------------------------------------------
270 DISP "CORRECTIONS TO DATA?-YES=1,NO=0";
280 INPUT G1
290 IF GI=0 THEN 390
300 DISP "PRESS PRT ALL KEY FOR RECORD.";
310 WAIT 7000
```

TABLE B2. (CONTINUED)

```
320 DISP "ENTER CORRECTION AS MATRIX ELEMENT";
330 WAIT 7000
340 DISP "ENTER CORRECT VALUE=?;EXEC., CONT.,EXEC.";
350 STOP
360 DISP "ANY MORE CORRECTIONS? YES=1,NO=0";
370 INPUT G1
380 IF G1=1 THEN 340
390 REM------------PRINT RAW DATA FOR THIS PT.------------------------------
400 PRINT
410 PRINT
420 PRINT
430 PRINT
450 WRITE (15,460)C[1],C[2],C[3],C[4],C[5],"  1/8 SCALE TJ TEST CELL"
460 FORMAT "RUN",F4.0,3X,"PT.",F4.0,2X,"DATE",F4.0,1X,F4.0,1X,F4.0,F4.0
480 PRINT
490 PRINT "CHANNEL 3       RAW  DATA  FILE "
500 FOR I=2 TO 34 STEP 16
510 WRITE (15,520)A[I],A[I+2],A[I+4],A[I+6],A[I+8],A[I+10],A[I+12],A[I+14]
520 FORMAT F8.0,2X,F8.0,2X,F8.0,2X,F8.0,2X,F8.0,2X,F8.0,2X,F8.0,2X,F8.0,2X
530 NEXT I
540 PRINT
550 I=50
560 WRITE (15,570)I,C[I],C[I+1],C[I+2],C[I+3],C[I+4],C[I+5],C[I+6]
570 FORMAT "CH.",F6.0,2X,F8.0,2X,F8.0,2X,F8.0,F8.0,2X,F8.0,2X,F8.0,2X,F8.0,2X
1200 REM------------STORE RAW DATA IN FILES TJRAW1-------------------------
1210 FILES TJRAW1
1220 DISP "STORE DATA? ENTER YES=1,NO=0";
1230 INPUT G1
1240 IF G1=0 THEN 1310
1260 MAT PRINT # 1,E1;A,C
1270 PRINT "THE RAW DATA IS STORED IN TJRAW1 RECORD # "E1
1280 PRINT "-----------------------------------------------------------------
```

TABLE B2. (CONTINUED)

```
1290 PRINT
1291 IF Z=0 THEN 40
1292 E1=E1+1
1293 GOTO 70
1300 GOTO 1320
1310 PRINT "THIS DATA WAS NOT STORED"
1320 GOTO 10
1330 END
```

TABLE B3. PROGRAM "HEW2" REDUCED DATA PROCESSING

```
10 REM----------********HEW2********----------------------------------------
20 REM---------DATA REDUCTION FOR 1/8 SCALE TURBOJET TEST CELL--------------
30 DIM A$[48],C$[56],P[10],Z[12],T[10]
40 DISP "ENTER RECORD # THIS POINT ";
50 INPUT E1
60 REM--------INPUT LOCAL BAROMETRIC PRESSURE  IN HG------------------------
70 DISP "BAROMETRIC PRESS (IN HG)=  ";
80 INPUT B0
90 REM--------------CHANNEL ASSIGNMENTS-------------------------------------
91 FILES TJRAW1
92 MAT READ # 1,E1;A,C
100 H3=(A[6]-A[8])*0.1
110 H4=(A[10]-A[12])*0.1
120 H6=(A[14]-A[16])*0.1
130 P3=(A[6]-A[4])*0.1*2.036/27.678+B0
140 P4=(A[10]-A[4])*0.1*2.036/27.678+B0
150 P6=(A[14]-A[4])*0.1*2.036/27.678+B0
160 FOR I=1 TO 3
170 P[I]=(A[16+2*I]-A[4])*0.1/13.5943+B0
180 NEXT I
190 FOR J=1 TO 12
200 Z[J]=(A[22+2*J]-A[4])*0.1/13.5943+B0
210 NEXT J
220 REM------------------TEMPERATURES----------------------------------------
225 REM CHANNEL C(50) IS THE MASTER REFERENCE OF THE THERMOCOUPLES
230 S=0.001*C[50]
240 T3=FNT(S)
250 S=0.001*(C[50]+C[51])
260 T4=FNT(S)
270 S=0.001*(C[50]+C[52])
280 T6=FNT(S)
290 FOR I=1 TO 4
300 S=(C[I+52]+C[50])*0.001
310 T[I]=FNT(S)
320 NEXT I
```

TABLE B3. (CONTINUED)

```
330 REM------------------------CONSTANTS---------------------------------------
340 D3=3.068
350 D6=6.065
360 02=2.152
361 03=2.149
370 06=4.246
380 04=2.301
390 05=2.454
400 REM----------------------FLOW RATE CALCULATIONS----------------------------
410 REM-----------FLOW RATE OF 3 IN PRIMARY LINE-------------------------------
420 A3=1+0.0005
430 B3=02/D3
440 Y3=1-0.05246*(0.41+0.35*B3↑4)*(H3/P3)
450 M3=1.0916678E-05+1.65811E-08*(T3)-6.496E-12*(T3)↑2
460 REM------------------------------BEGIN FLOW RATE ITERATION-----------------
470 W9=2
480 R=48*W9/(PI*D3*M3)
490 K3=FNR(R)
500 REM K5=FNE(E)
510 REM K7=FNF(F)
520 W8=0.1148235*02↑2*A3*K3*Y3*SQR(P3*H3/(T3+460))
530 W7=ABS(W8-W9)
540 IF W7<1E-05 THEN 570
550 W9=W8
560 GOTO 480
570 W3=W8
```

TABLE B3. (CONTINUED)

```
580 REM-----------------------FLOW RATE FOR 8 IN SECONDARY LINE-----------------
590 A4=1+0.0005
600 B4=03/D3
610 Y4=1-0.05246*(0.41-0.35*B4↑4)*(H4/P4)
620 M4=1.0916678E-05+1.85811E-08*(T4)-6.496E-12*(T4)↑2
630 REM-------------------BEGIN FLOW RATE ITERATION----------------------------
640 W9=4
650 R=48*W9/(PI*D3*M4)
660 K4=FNR(R)
670 W8=0.1148235*03↑2*A4*K4*Y4*SQR(P4*H4/(T4+460))
680 W7=ABS(W8-W9)
690 IF W7<1E-05 THEN 720
700 W9=W8
710 GOTO 650
720 W4=W8
730 REM------------------FLOW RATE FOR 6 IN INTAKE LINE-------------------------
740 A6=1+0.0005
750 B6=06/D6
760 Y6=1-0.05246*(0.41-0.35*B6↑4)*(H6/P6)
770 M6=1.0916678E-05+1.85811E-08*(T6)-6.496E-12*(T6)↑2
780 REM---------------------BEGIN FLOW RATE ITERATION--------------------------
790 W9=5
800 G=48*W9/(PI*D6*M6)
810 K6=FNG(G)
820 W8=0.1148235*06↑2*A6*K6*Y6*SQR(P6*H6/(T6+460))
830 W7=ABS(W8-W9)
840 IF W7<1E-05 THEN 870
850 W9=W8
860 GOTO 800
870 W6=W9
```

TABLE B3. (CONTINUED)

```
880 REM--------------------PRINT OUT OF CALCULATED FLOW RATES--------------------
890 WRITE (15,900)C[1],C[2],C[3],C[4],C[5]"    1/8 SCALE TJ TEST CELL"
900 FORMAT "RUN",F4.0,3X,"PT.",F4.0,2X,"DATE",F4.0,1X,F4.0,1X,F4.0,F4.0
905 PRINT "LOCAL BAROMETRIC PRESS=   "B0"IN HG"
910 PRINT "FLOW RATE OF 3 IN PRI LINE=   "W3
920 PRINT "FLOW RATE OF 3 IN SEC LINE=   "W4
930 PRINT "FLOW RATE OF 6 IN INTAKE LINE=  "W6
935 PRINT "TOTAL FLOW RATE"
936 PRINT W3+W4+W6
940 PRINT "DP/PRI                DP/SEC          DP/SUCT       (IN H2O)"
950 PRINT H3;H4;H6
951 PRINT "P1/PRI            P1/SEC            P1/SUCT              (IN HG)      "
952 PRINT P3;P4;P6
953 PRINT "T PRI              T SEC              T SUCT     (DEG F)"
954 PRINT T3;T4;T6
960 PRINT "CELL PRESSURES"
970 FOR I=1 TO 3
980 PRINT P[I]
990 NEXT I
1000 PRINT "AUGMENTOR TUBE PRESSURES"
1010 FOR I=1 TO 12
1020 PRINT Z[I]
1030 NEXT I
1040 PRINT " CELL TEMPS AND AUGMENTOR TEMPS"
1050 FOR I=1 TO 4
1060 PRINT T[I]
1070 NEXT I
1080 REM--------------STORE REDUCED DATA----------------------------------------
1090 DISP "STORE DATA?  ENTER YES=1, NO=0";
1100 INPUT G1
1110 IF G1=0 THEN 1190
1120 FILES TJRED1
1130 PRINT #1,E1;W3,W4,W6,H3,H4,H6,P3,P4,P6,T3,T4,T6
1140 MAT PRINT # 1,E1;P,Z,T
1145 PRINT
1150 PRINT "THE REDUCED DATA IS STORED IN TJRED1 RECORD # "E1
1160 PRINT "-----------------------------------------------------------------"
```

TABLE B3. (CONTINUED)

```
1170 PRINT
1180 GOTO 1210
1190 PRINT "THIS DATA HAS NOT BEEN STORED"
1200 GOTO 30
1210 STOP
1220 END
1240 DEF FNT(S)=34.354583+42.351777*S-0.402489*S↑2
1300 DEF FNR(R)
1320 R0=0.710635-0.000297*(R*1E-04)+0.000002*(R*1E-04)↑2
1360 RETURN R0
1370 REM DEF FNE(E)
1390 E2=0.750917-0.000387*(E*1E-04)+0.000002*(E*1E-04)↑2
1430 REM RETURN E2
1440 REM  DEF FNF(F)
1460 F2=0.807446-0.000538*(F*1E-04)+0.000003*(F*1E-04)↑2
1480 F1=F2
1490 F0=F1
1500 REM  RETURN F2
1510 DEF FNG(G)
1530 G2=0.710833-0.000303*(G*1E-04)+0.000002*(G*1E-04)↑2
1570 RETURN G2
```

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1. Advisory Group for Aerospace Research and Development, Report 125, "Pollution Control of Airport Engine Test Facilities", by D. L. Bailey, P. W. Tower, and A. E. Fuhs, April 1973.

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